UNIVERSITY OF
SOUTHERN CALIFORNIA
SCHOOL OF ENGINEERING

MECHANICAL ENGINEERING DEPARTMENT

12

ABSTRACTS

1981 AFOSR CONTRACTORS MEETING
ON AIR BREATHING COMBUSTION DYNAMICS
AND EXPLOSION RESEARCH

November 16 - 20, 1981

Clearwater, Florida

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RAM JETS	REACTING FLOW DIAGNOSICS	COMBUSTION INSTABILITY
GAS TURBINES	IGNITION	PARTICLE DYNAMICS
COMBUSTION MODELING	HOMOGENEOUS COMBUSTION	PREMIXING/PREVAPORIZING COMBUSTION
FUEL-AIR EXPLOSIONS	HETEROGENEOUS COMBUSTION	CATALYTIC COMBUSTION
EXPLOSION	FLAME EXTINGUISHMENT	RAPID EXPANSION BURNING

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The report consists of a collection of expanded abstracts of the numerous research progress reports given by AFOSR supported contractors on the Air Force basic research program on Energy Conversion Related to Air-Breathing Propulsion and Explosions and of invited papers from other governmental agencies and contractors. These papers presented over a five-day period composed the 1981 contractors meeting on Air-Breathing Combustion Dynamics and Explosion Research. The principal investigators and their organizational association are also identified.

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AGENDA

1981 AFOSR CONTRACTORS MEETING
on
AIRBREATHING COMBUSTION DYNAMICS AND EXPLOSION RESEARCH

November 16-20, 1981

Surfside Holiday Inn
Clearwater Beach, Florida

Monday AM Session

8:00 Official Registration -- Surfside Holiday Inn

8:30 Welcome -- AFOSR Program Manager and Meeting Coordinator

B.T. Wolfson

8:35 Morning Chairman

B.T. Wolfson
Air Force Office of Scientific Research (AFOSR)

8:40 Future Directions in AFOSR Energy Research

M. Salkind
Director of Aerospace Sciences Directorate
US Air Force Office of Scientific Research (AFOSR)

9:05 Army Supported Research and Development Trends and Research Needs in Airbreathing Combustion, Kinetics and Explosions

R. Singleton
US Army Research Office (ARO)

9:30 Navy Supported Research and Needs in Airbreathing Combustion, Kinetics and Explosions

A. Wood
US Office of Naval Research (ONR)

9:55 NASA In-House and Supported Research, Development Trends and Research Needs in Airbreathing Combustion

L. Diehl
NASA - Lewis Research Center

10:20 BREAK

10:35	**DOE Supported Research and Needs in Basic Energy Sciences Associated with Airbreathing Combustion Dynamics, Kinetics and Explosions** W. Adams Department of Energy/Office of Basic Energy Sciences
11:00	NSF Supported Research and Needs in Basic Energy Sciences Associated with Airbreathing Combustion, Kinetics and Explosions R. Rostenbach National Science Foundation
11:25	UK Supported Research, Development Trends and Research Needs in the Areas of Airbreathing Combustion, Kinetics and Explosions J. Hooper (or alternate) British Embassy/Defense Research Staff
11:50	APL In-House and Supported Research, Development Trends and Research Needs Associated with Airbreathing Combustion Technology T. Curran Chief Scientist - Aero Propulsion Laboratory AF Wright Aeronautical Laboratories (AFWAL)
12:15	LUNCH

Monday PM Session

1:45	Afternoon Chairman R. Singleton US Army Research Office (ARO)
1:50	Overview of the Assessment of Fundamental Combustion Technology for Ramjet Applications R. Edelman Science Applications Inc.
2:15	Overview of the ONR/AFOSR Coloquium on Turbulent Reacting Flow Processes S.N. B. Murthy Purdue University
2:40	APL In-House Supported Research, Development Trends and Needs in Ramjet Combustion Craig & D. Stull Aero Propulsion Laboratory AF Wright Aeronautical Laboratories (AFWAL)
3:05	BREAK

3:30 APL In-House and Supported Research, Development Needs in Turbo Propulsion Combustion Technology

J. Petty
Aero Propulsion Laboratory
Wright Aeronautical Laboratories (AFWAL)

3:45 AFRPL In-House and Supported Research and Needs Associated with Multiphase Chemically Reacting Flow Systems.

D. Mann
AF Rocket Propulsion Laboratory

4:10 ADJOURN

Tuesday AM Session

8:30 Morning Chairman

J. Petty
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

8:35 Injection, Atomization, Ignition and Combustion of Liquid and Multiphase Fuels in High-Speed Air Streams

J. Schetz
VPI and State University

9:00 Turbulent Mixing and Combustion in High Speed Flows

C.Peters & R. Rhodes
AEDC/ARO

9:25 Fundamental Modeling of 3-Dimensional Multiphase Reacting Flow Systems

J. Swithenbank
Sheffield University, England

9:50 Fundamental Studies of Chemical Reactions in High Speed Turbulent Flows

H. Liepmann, Rosko and Dimotakis
California Institute of Technology

10:15 BREAK

10:30 Mixing, Ignition and Combustion in Flowing Reacting Fuel-Air Mixtures

R.B. Edelman & P.T. Harsha
Sciences Applications Inc.

10:55 Turbulent Mixing and Combustion of Multi-Phase Reacting Flows in Ramjet and Ducted Rocket Environments

K. Schadow
Naval Weapons Center

11:20 Fundamental Studies of High Energy - High Density Fuel Ignition and Combustion in Ramjet and Ducted Rocket Environments

M. King
Atlantic Research Corporation

11:55 LUNCH

Tuesday PM Session

1:30 Afternoon Chairman

D.F. Stull
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

1:35 Research on Supersonic and Dual Mode Combustion at NASA-Langley Research Center

G.B. Northam
NASA-Langley Research Center

2:00 Combustor Inlet Interactions and Modeling of Dual - Combustion Hypersonic Ramjet Engine

P. Walthrup
Applied Physics Lab/Johns Hopkins University

2:25 Flame Efficiency, Stabilization and Performance in Airbreathing Combustors

A.M. Mellor
Purdue University/KVB-Research Cottrell

2:50 Fundamental Studies of Flame Holding Phenomena on High Speed Reacting Flow Systems

W. Strahle
Georgia Institute of Technology

3:15 BREAK

3:30 Mechanisms of Exciting Pressure Oscillations in Ramjet Engine Environments

F. Culick
California Institute of Technology

3:55 Basic Instability Mechanisms in Chemically Reacting Turbulent Flows

T.Y. Toong
Massachusetts Institute of Technology

4:20 Critical Evaluation of High Temperature Kinetic Data for Combustion and Exhaust Reactions

L.H. Gevantman
National Bureau of Standards, Gaithersburg, MD

4:45 Electrostatic Atomization of Hydrocarbons Spray Patternation Studies

Arnold J. Kelly
Exxon Research & Engineering, Linden, N.J.

5:10 ADJOURN

Wednesday AM Session

8:30 Morning Chairman

C. Martel
AF Engineering Service Center/Tyndall AFB Florida

8:35 Air Force 10 Year Plan and Associated Activities

Maj. B. Lenz
ODCS (Logistics & Engineering)/Pentagon

9:00 Navy Mobility Fuel Research and Development Program

A. Roberts
Naval Material Command/Energy and Natural Resources Division

9:25 Air Force Research and Development Programs and Future Requirements in Non-Mobility (Facility) Energy Technology

S. Hathaway
AF Engineering Services Center/Tyndall AFB Florida

9:50 Research in Energy Conservation in the DOE Energy Conservation Program

K. Bastress
Department of Energy
Energy Conservation and Utilization Technology Division

10:15 BREAK

10:30 Use of Alternate Fuels in Commercial Turbines and Boilers and Applications to Air Force Problems

J. Kliegel & R. Thompson
KVB - Research Cottrell

10:55 AFESC Supported Research and Needs Associated with Gas Turbine Engine Emissions and Other Combustion Related Problems

Capts. T. Slankas & H. Clewell
AF Engineering Services Center/Tyndall AFB Florida

11:20 Status of the Utilization of New and Alternative Fuels in Airbreathing Turbine and Ramjet Engines

C. Martel, C. Delaney, J. McCoy & Capt. Potter
Aero Propulsion Laboratory
Wright Aeronautical Laboratories (AFWAL)

11:55 LUNCH

Wednesday PM Session

1:30 Afternoon Chairman

Capt. T. Slankas
AF Engineering Services Center/Tyndall AFB Florida

1:35 Propulsion, Oxidation and Reaction Kinetics of Hydrocarbons and Alternative Fuels

I. Glassman & F. Dryer
Princeton University

2:00 Ionic Mechanisms of Carbon Formation in Flames

H.F. Calcote
Aerochem Research Laboratories, Inc.

2:25 Mechanisms of Exhaust Pollutant and Plume Formation in Continuous Combustion

G.S. Samuelson
University of California - Irvine

2:50 Hydrocarbon Droplet and Particulate Formation, Combustion and Extinction Phenomena in Turbulent Reacting Flows

F.A. Williams
University of California - La Jolla/Princeton University

3:15 BREAK

3:30 Single Droplet Combustion Studies of Carbon Slurry Fuels

G.M. Faeth
Pennsylvania State University

3:55 Thermodynamics of Organic Compounds

W.D. Good
DOE Bartlesville Energy Technology Center

4:20 Gas Interaction and Liquid Phase Reactions Associated with Swirl Combustion and Explosions

P. R. Choudhury & M. Gerstein
University of Southern California, Los Angeles

4:55 ADJOURN

7:00 SOCIAL -- Surfside Holiday Inn

8:00 BANQUET -- Surfside Holiday Inn

Thursday AM Session

8:00 Morning Chairman

D.M. Roquemore
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories

8:05 Research at LLL on Advanced Diagnostic Techniques and Airbreathing Combustion Dynamic Related Phenomena

D.L. Hartley
Sandia National Laboratory

8:30 AFOSR Supported Research and Needs in the Area of Advanced Diagnostics and Instrumentation for Chemically Reacting Flow Systems

L. Caveny
Air Force Office of Scientific Research (AFOSR)

9:00 Studies of Combustion Processes in APL Combustion Research Facility

R.P. Bradley & D.M. Roquemore
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

9:25 Coherent Structures in Turbulent Flames

N. Chigier
Sheffield University/Carnegie-Mellon University

9:50 Measurement of Turbulence in Combustion Systems by Raleigh Scattering

L. Talbot and F. Robbins
University of California - Berkeley

10:15 BREAK

10:30 Laser Velocity Measurements and Analysis of Turbulent Flows with Combustion

W. Stevenson
Purdue University

10:55 Combustion Diagnostics in Practical Combustion Systems Employing the CARS Technique

L. Goss
Systems Research Laboratories

11:20 High Temperature Catalytic Combustion

F. Bracco
Princeton University

11:55 LUNCH

Thursday PM Session

1:15 Afternoon Chairman

B. Levine
National Bureau of Standards, Gaithersburg, MD

1:20 Radiation Enhanced Ignition, Combustion and Flame Stabilization

M. Lavid
Exxon Research and Engineering Company

1:45 Interfacial Chemical Reactions in Flow Systems

D.F. Rosner
Yale University

2:10 NBS In-House and Supported Research, Development Trends and Research Needs in Airbreathing Combustion, Kinetics, Explosion and Fire Protection

R. Levine
National Bureau of Standards, Gaithersburg, MD

2:35 APL Supported Research, Development Trends and Needs in Aircraft Fire and Explosion Technology

J. Manheim
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

3:00 BREAK

3:15 Ignition of Fuel Sprays by Hot Surfaces and Stabilization of External and Void Space Aircraft Fires

A.H. Lefebvre, J.G. Skifstad & S.N.B. Murthy
Purdue University

3:40 Ignition of Fuels by Incendiary Metal Particles

W.A. Sirignano
Carnegie-Mellon University

4:05 Executive Session
(AFOSR Contractors/Grantees ONLY)

5:00 ADJOURN

Friday AM Session

8:30 Morning Chairman

J. Manheim
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

8:35 Ignition of Fuels Under High Intensity Laser Radiation

T. Kashiwagi, W. Braun & M. Scheer
National Bureau of Standards, Gaithersburg, MD

9:00 Reactions of Hydrocarbon Gases Initiated by a Pulse Infrared (CO_2) Laser

G.B. Skinner
Wright State University

9:25 AFATL Combustion and Explosion Research and Development Program and Future Requirements Associated with Conventional Weapons

M. Zimmer
AF Armament Test Laboratory/Eglin AFB Florida

9:50 Air Force In-House and Supported Research and Development and Future Requirements in Unconfined Fuel - Air Explosions

G. Parsons
AF Armament Test Laboratory/Eglin AFB Florida

10:15 BREAK

10:30 Research on Detonation Tube Study Analysis of Explosion Phenomena

A. Tullis
Illinois Institute of Technology Research Institute

10:55 Detonation Characteristics of Multiphase Heterogenous Distributed Fuel - Air Clouds

C.W. Kauffman & J.A. Nicholls
University of Michigan

11:20 National Academy of Science Panel on Grain Mill Explosions - Problems, Research Needs and Approaches

C.W. Kauffman
University of Michigan

11:55 LUNCH

Friday PM Session

1:30 Afternoon Chairman

G. Parsons
AF Armament Test Laboratory - Eglin AFB Florida

1:35 Mechanisms of Direct Shockless Initiation of Unconfined Fuel - Air Detonations

J. Lee, R. Knystautas, I. Moen & C. Guirao
McGill University - Canada

2:00 Detonation Initiation and Propagation in Chemically Sensitized Unconfined Fuel - Air Mixtures

G. Von Elbe, E.T. McHale, R. Fry
Atlantic Research Corporation

2:25 Ignition, Acceleration, Stability and Limits of Detonation

H. Wagner & W. Jost
University of Gottengen

2:50 Effect of Concentration Gradients and Variable Reaction Kinetic Rates on Detonation Properties of Distributed Reactive Fuel - Air Clouds

H. Edwards
University of Wales - England

3:15 BREAK

3:30 Ignition Combustion, Detonation and Quenching of Flames and Detonations in Reactive Mixtures and Related Phenomena

R. Edse
Ohio State University

3:55 Theoretical Modeling and Prediction of Detonation Properties in Dispersed Powdered High Explosive - Air Clouds

K. Frair
Virginia Polytechnic and State University

4:20 Accidental fuel air Clouds, then Shapes and Burning Properties

D. Lewis
England

4:45 ADJOURN

AGENDA

1981 AFOSR CONTRACTORS MEETING
on
AIRBREATHING COMBUSTION DYNAMICS AND EXPLOSION RESEARCH

November 16-20, 1981

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Clearwater Beach, Florida

Monday AM Session

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8:35	Morning Chairman B.T. Wolfson Air Force Office of Scientific Research (AFOSR)
8:40	Future Directions in AFOSR Energy Research M. Salkind Director of Aerospace Sciences Directorate US Air Force Office of Scientific Research (AFOSR)
9:05	Army Supported Research and Development Trends and Research Needs in Airbreathing Combustion, Kinetics and Explosions R. Singleton US Army Research Office (ARO)
9:30	Navy Supported Research and Needs in Airbreathing Combustion, Kinetics and Explosions A. Wood US Office of Naval Research (ONR)
9:55	NASA In-House and Supported Research, Development Trends and Research Needs in Airbreathing Combustion L. Diehl NASA - Lewis Research Center
10:20	BREAK

FUTURE DIRECTIONS IN AFOSR ENERGY RESEARCH

Dr. M. Salkind
US Air Force Office of Scientific Research (AFOSR)

ABSTRACT NOT AVAILABLE

ARMY SUPPORTED RESEARCH IN AIRBREATHING COMBUSTION AND EXPLOSIONS

Robert E. Singleton
Director, Engineering Sciences Division
U. S. Army Research Office

Fundamental studies in the combustion sciences supported by the Army Research Office are focussed on those combustion areas relevant to both diesel and gas turbines, fuels, propellants and explosives. However, in view of the interest of this community, the following discussion is confined to aeropropulsion related topics. These research studies are concerned with catalytic surface effects, turbulent combustion models, flames in sprays and novel nonintrusive diagnostic techniques.

Of basic importance to any combustor design is the understanding of unsteady and steady flame propagation through fuel air sprays. Accordingly, models for such heterogeneous combustion processes characteristic of gas turbine combustors have been developed and a unique uniform spray injector has been designed to obtain fundamental measurements for flames in sprays with systematic changes in spray parameters; for example, uniform droplet size, distribution and velocity. Unique turbulent combustion models based on a combined Monte Carlo/finite difference method is being developed in which the mean momentum and turbulence model equations are being solved by finite-difference techniques, while the reaction is treated by solving the joint probability density function by a Monte Carlo method. So far, the Monte Carlo method has been applied to two flows: an inert, two-dimensional mixing layer and a premixed propane/air flame. Effort is underway to attempt an extension of this procedure for the more complex flow fields, species concentrations and finite-rate chemistry in two-dimensional combustor configurations. Another investigation is concerned with the effect of turbulent intensity and turbulent scale on flame speed at various equivalence ratios and pressures in a simple flat flame geometry. Novel diagnostic techniques are also being examined for measuring heat release rates in gas turbine combustor flames. Since heat release rate fluctuations through a flame are linked to the acoustic output, the feasibility of using combustion noise as a nonintrusive combustion diagnostic has been examined for open premixed turbulent flames and is now being carried out for a gas turbine combustor configuration.

Catalysts such as platinum or nickle oxide can lower the ignition temperatures of a given fuel-air mixture by several hundred degrees and extend the ignition limits in both the rich and lean directions. Such capabilities are of obvious significance to combustor development, particularly in view of the anticipated degradation in fuel quality in the future. Consequently, several investigations are ongoing for determining reactive rate data for various catalysts. These measurements will serve as checks for an analytical model for predicting surface ignition temperatures and distributions of chemical species and temperature during steady state catalytic combustion. This analytical effort considers transient solutions of laminar boundary layer flows with chemical reactions in order to study the transient and steady-state competition of catalytic and homogeneous reactions. Another research investigation is concerned with the effect of substrate configuration and concentration of active metal on reaction rate for several typical hydrocarbons. Follow-on tests will involve the use of active metal-coated metal substrates to determine the effect

of metal and metal mixtures (e.g., platinum/palladium) on the interaction and extent of reaction for varying composition of fuel mixtures.

Research on gas turbine combustors is also carried out at the Propulsion Laboratory of the Research and Technology Laboratories, U. S. Army Aviation Research and Development Command, colocated with the NASA Lewis Research Center in Cleveland, Ohio. For completeness, a summary of these activities is also provided.

Anticipated higher pressures and temperatures for combustor operation in small gas turbines have highlighted the need to develop primary-zone analytical design methodology. Thus, activities for obtaining primary-zone data and development of empirical models of the combustion process in this zone are underway. As a companion study, several advanced fuel injector designs have been examined for their effects on the primary combustion zone, recirculation, flame stabilization, mixing and wall quenching phenomena. Of course, higher temperatures require better coating mechanisms for liner walls or better wall construction to withstand such harsh environments. One such approach is the utilization of plasma-sprayed ceramic on a porous metal substrate. This construction allows for substantial reductions in wall temperature with much less penalty for supplying cooling air. Another concept offering substantial reductions in wall temperature for combustion designs is a counterflow film-cooled combustor which utilizes offset fin material to enhance heat transfer close to the primary combustion zone and counterflow arrangements for cooling the downstream portions of the combustor walls.

The Army Research Office supports a singular project on explosions concerned with the structure and characteristics of heterogeneous detonation. A detailed analytical study of the influence of droplet breakup and the accompanying wake explosions upon the propagation of spray detonations is in progress, the key problem being to define a suitable induction zone length for a spray detonation. Experimentally, a vertical detonation tube and associated instrumentation have been developed to make measurements for a variety of droplet sizes, equivalence ratios, velocity deficits, droplet material vapor pressures, cloud gaps, and initiating shock strengths. Results of this study are expected to contribute to an understanding of blast and detonation phenomena associated with fuel-air explosive munitions and permit one to more realistically assess hazards due to accidental dispersion of fuel or other energetic materials.

NAVY SUPPORTED RESEARCH AND NEEDS IN AIRBREATHING COMBUSTION, KINETICS AND EXPLOSIONS

Dr. A. Wood
US Office of Naval Research (ONR)
(202/692-4407)

ABSTRACT NOT AVAILABLE

NASA IN-HOUSE AND SUPPORTED RESEARCH
DEVELOPMENT TRENDS AND RESEARCH NEEDS IN AIRBREATHING COMBUSTION

Larry A. Diehl

Chief, Combustion Branch
Aerothermodynamics and Fuels Division
NASA Lewis Research Center

The combustion research and technology programs that are conducted and supported by the Combustion Branch cover a wide spectrum from the most basic studies of combustion phenomena to the evaluation of advanced combustor concepts. The overall thrust of these efforts is to provide the combustor design engineer with the information and data required to design and develop advanced combustion systems that have high performance, improved durability, while achieving fuel flexibility and reduced emissions. The research is focused on achieving a basic understanding and analytical representation of the fundamental aerodynamic and chemical kinetic phenomena governing the combustion process, the development of analytical models for predicting the internal aerothermodynamic performance of combustors, and the identification and evaluation of advanced combustors and combustor components.

The overall program of combustion research and technology is conducted in-house at the Lewis Research Center, through university grants, and through industry contracts. Within the Combustion Branch, research is carried out by the Combustion Fundamentals Section, the Component Research Section, and the Combustor Research Section. In addition, some fundamental combustion research is also conducted within the Kinetics and Thermodynamics Section of the Fuels Branch; Aerothermodynamics and Fuels Division.

The Combustion Fundamentals Section is responsible for analytical modeling of combustor/combustion processes and the development and application of advanced numerical techniques. In addition, this Section is responsible for the conduct of fundamental combustion experiments including detailed experiments designed to provide benchmark data for model validation. The work of this group has experienced considerable growth over the past couple of years. In a recent new assignment, this Section has been made responsible for the management and conduct of the combustor portion of the Hot Section Technology (HOST) Program.

The HOST program will involve a rather extensive program of industry contracts to improve the predictive capability of existing combustor models and will also undertake a program of in-house research in the areas of combustor flame radiation and liner cyclic life.

The Component Research Section is involved with the design and evaluation of small and large combustor components including fuel injectors, combustor primary zone design criteria, and advanced liner cooling technology including the adaptation of ceramics. This Section is also responsible for a growing program of research associated with small gas turbine engine combustion systems for commuter aircraft, rotorcraft, and general aviation. Management and conduct of supporting research and technology for DOE sponsored programs in stationary power generation, automotive gas turbine, and automotive stirling engines complete the responsibilities of this group.

The Combustor Research Section is responsible for the design and evaluation of full scale advanced combustor concepts. In-house programs involve concepts which embody full swirl, variable geometry and multi-zone burning. A high pressure high temperature combustion system is also currently under development. In addition, contract studies with the major engine manufacturers are currently evaluating concepts which employ premixed-prevaporized combustion, catalytic combustion, and a variety of combustor configururation intended to provide fuel-flexible operation.

The Kinetics and Thermodynamics Section is concerned with the development and maintenance of a thermodynamic properties data bank, the design and conduct of fundamental experiments to evaluate fuel property effects on chemical reaction mechanisms, and the development and verification of chemical reaction models.

The presentation will outline and discuss the programmatic activities that are currently underway or planned within the groups outlined above.

DOE SUPPORTED RESEARCH AND NEEDS IN BASIC ENERGY SCIENCES ASSOCIATED WITH AIRBREATHING COMBUSTION DYNAMICS, KINETICS AND EXPLOSIONS

W. Adams
Department of Energy/Office of Basic Energy Sciences

<u>ABSTRACT NOT AVAILABLE</u>

NSF SUPPORTED RESEARCH AND NEEDS IN BASIC ENERGY SCIENCES ASSOCIATED WITH AIRBREATHING COMBUSTION, KINETICS AND EXPLOSIONS

Dr. Royal Rostenbach
National Science Foundation
(202/357-9606)

ABSTRACT NOT AVAILABLE

UK SUPPORTED RESEARCH
DEVELOPMENT TRENDS AND RESEARCH NEEDS IN THE AREAS OF AIRBREATHING COMBUSTION, KINETICS AND EXPLOSIONS

J. Hooper (or alternate)
British Embassy/Defense Research Staff
Washington D.C.

<u>ABSTRACT NOT AVAILABLE</u>

APL IN-HOUSE AND SUPPORTED RESEARCH, DEVELOPMENT TRENDS AND RESEARCH NEEDS ASSOCIATED WITH AIRBREATHING COMBUSTION TECHNOLOGY

T. Curran
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories

ABSTRACT NOT AVAILABLE

Monday PM Session

1:45 Afternoon Chairman

R. Singleton
US Army Research Office (ARO)

1:50 Overview of the Assessment of Fundamental Combustion Technology for Ramjet Applications

R. Edelman
Science Applications Inc.

2:15 Overview of the ONR/AFOSR Coloquium on Turbulent Reacting Flow Processes

S.N. B. Murthy
Purdue University

2:40 APL In-House Supported Research, Development Trends and Needs in Ramjet Combustion

Craig & D. Stull
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

3:05 BREAK

3:20 APL In-House and Supported Research, Development Needs in Turbo Propulsion Combustion Technology

J. Petty
Aero Propulsion Laboratory
Wright Aeronautical Laboratories (AFWAL)

3:45 AFRPL In-House and Supported Research and Needs Associated with Multiphase Chemically Reacting Flow Systems.

D. Mann
AF Rocket Propulsion Laboratory

4:10 ADJOURN

ASSESSMENT OF FUNDAMENTAL COMBUSTION TECHNOLOGY FOR RAMJET APPLICATIONS (N60530-79-C-0029)

P. T. Harsha, R. B. Edelman, R. C. Farmer

Science Applications, Inc.
Combustion Science and Advanced Technology Department
9760 Owensmouth Avenue
Chatsworth, CA 91311

Although ramjet research and development programs have been pursued for nearly 40 years, continuously changing mission requirements have led to discontinuous efforts in many key areas. This history contrasts strongly with the continuous development process which has taken place in gas turbine combustion technology. The effect of the interruptions in ramjet technology efforts is that significant developments and technology advancements are in danger of becoming lost (or of being overlooked). This concern, and a collateral conviction that significant new information relevant to ramjet combustors and combustion technology is continuously being developed in other areas of research but is not being applied to ramjets, led to this technology assessment under Joint Army-Navy-NASA-Air Force (JANNAF) sponsorship. The results of this program are a consolidation, a critical review, and an assessment of the available airbreathing combustion technology base pertinent to ramjet technology for both subsonic and supersonic combustion ramjets. The emphasis in this program is on combustor and combustion *technology;* the work is not concerned with reviewing, assessing, or criticizing the results of previous development programs. Instead, the intent of the current program is the assessment of the available technology base. Some of this technology base is he result of previous development programs, but much of it also arises from independent research investigations. In the present program, the objective is to provide a resource of information applicable to current and future ramjet development work and to identify those areas in which fundamental technology gaps exist.

The information contained in this report is applicable to a wide variety of propulsion systems that use ram air as the primary oxidizer source. Figure 1 shows the generic systems of interest, which include conventional and advanced (integral rocket) liquid fueled subsonic combustion ramjets, solid fueled systems including ducted rockets and solid fuel ramjets, and supersonic combustion systems including internal- and external-burning configurations.

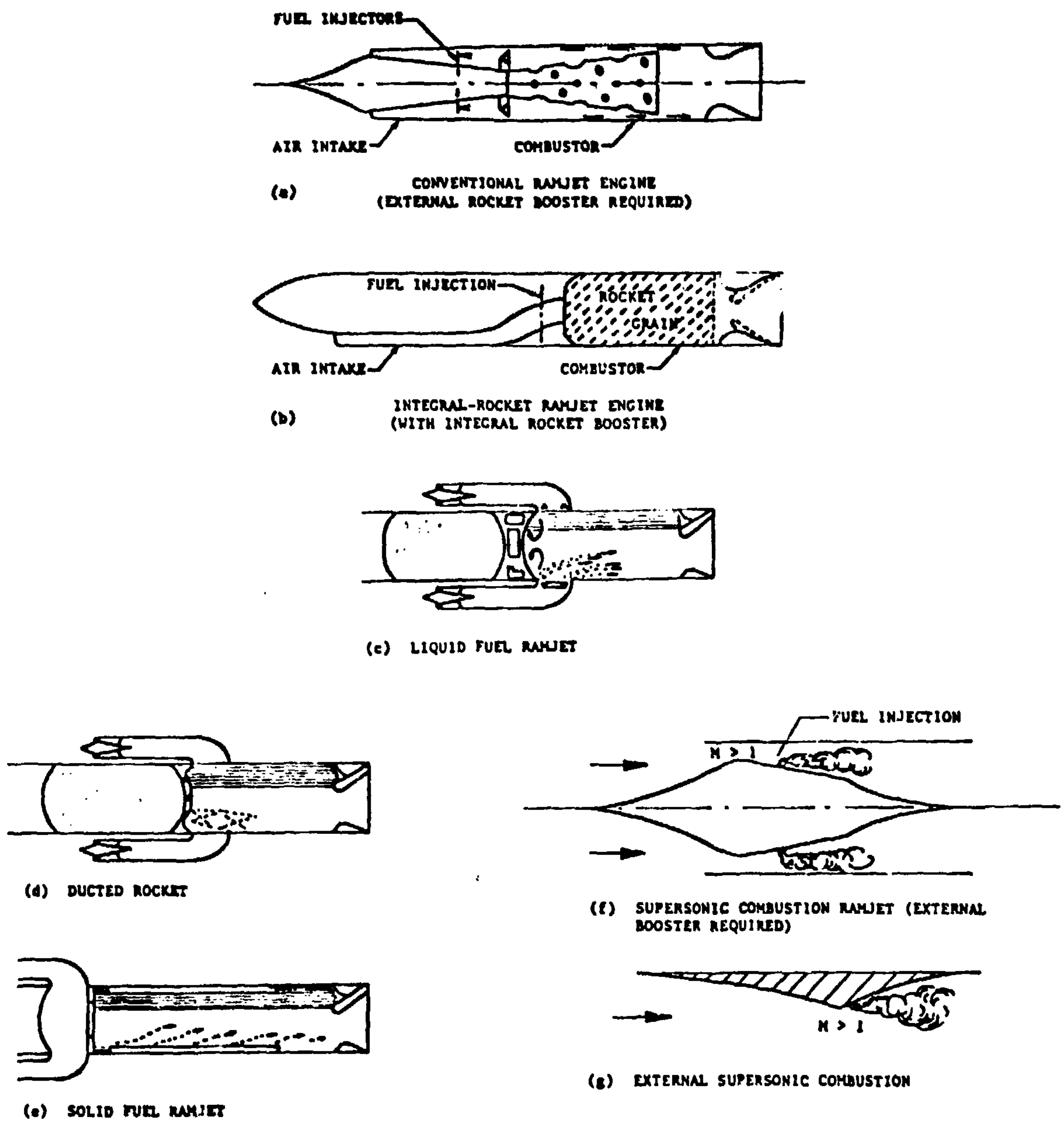

FIGURE 1. Various Airbreathing Propulsion Systems Relevant to Present Assessment.

The approach to assessment of the available technology base relevant to these types of systems involves a somewhat arbitrary division into six major categories, for both subsonic and supersonic combustion:

- Fuels
- Fuel-air mixing
- Ignition and flame stabilization
- Flame propagation
- Combustion instability
- Combustor technology

This division is arbitrary because all of these subjects involve processes which are, in the context of ramjet combustors, interrelated; but it has been defined in order to conform broadly to the sequence of events or processes which can occur in the combustor and to the basic areas of research which have an effect on ramjet combustor technology. In each of these areas the emphasis in on the segment of the subject which has direct influence on the combustor performance; thus, for example, the storage properties of fuels, which affect the overall ramjet system constraints, but do not directly affect the combustor, are not of interest here. On the other hand, fuel additives, designed to enhance fuel storability, are of interest if they affect the combustion characteristics of the fuel.

Sources of information for this review and assessment include contractor reports, JANNAF proceedings, and technical journals and proceedings such as those of the Combustion Institute. In addition to this literature, information from engine manufacturers and industrial, government, and university laboratories has been solicited by means of a detailed questionnaire. A total of 72 questionnaires was sent out to a distribution that comprised approximately 40% university and industrial laboratories, 40% government laboratories and research and development centers, and 20% engine manufacturers. The response to this solicitation was extremely good, both in the number of responses received and in the quality of the information provided; this information, as requested, included both additional literature sources and comments regarding the use of gaps in the available technology.

Following Section 1, Introduction, the subsequent sections of the report address each of the six categories. The topic of Section 2, fuels, includes

a compilation of fuel properties, discussions of fuel combustion characteristics, and an assessment of the technology base relevant to the determination of fuel properties and combustion characteristics (including chemical kinetic models) for ramjet applications. In Section 3, fuel-air-mixing, the mechanisms involved in injection of gaseous and liquid fuels and the subsequent mixing and vaporization processes are considered. The mechanisms involved in ignition and flame stabilization are the subject of Section 4, which is concerned with the assessment of available techniques for the establishment of ignition and flame stabilization boundaries for ramjet operation. Premixed and heterogeneous ignition and flame stabilization phenomena pertinent to subsonic and supersonic combustion gaseous and liquid fueled ramjets are considered in detail, as are the ignition and flame stabilization phenomena peculiar to solid-fuel ramjets. This assessment is followed in Section 5 by an evaluation of the technology base relevant to flame propagation phenomena in ramjets; here available data are reviewed, and methods which can be used to assess and predict ramjet flame propagation rates are discussed. Combustion instability phenomena which are of continuing concern in ramjet applications, are described in Section 6. Techniques which can be used in combustor development to provide high levels of combustion intensity exacerbate instability problems in ramjets, and this section focuses primarily on the available technology for the assessment and control of combustion instabilities in ramjets. The individual mechanisms and processes described in each of these sections are combined in a ramjet environment; Section 7, Combustor Technology, is concerned with the data and methods which are currently available to evaluate the effects of this combination. Inherent in this aspect of ramjet technology is the subject of scaling.

Each section of the report is structured to provide maximum utilization of the information that has been compiled while addressing the evaluation and assessment of this information. The composition of the material includes the source and type of information, the requirement which led to the existing technology base, and the enhancement of this technology base through the transfer and utilization of information from other combustion-related research. Thus, while the material contained in this report is designed to be of interest to the ramjet combustor designer, the result of this work is not

intended to be a ramjet combustor design handbook. Instead, the compilation and assessment of available technology data and the identification of technology gaps are intended to be of value to all those working in ramjet combustion technology, including engine manufacturers and industrial, government, and university research laboratories.

OVERVIEW OF THE ONR/AFOSR COLOQUIUM ON TURBULENT REACTING FLOW PROCESSES

S.N. Murthy
Purdue University

ABSTRACT NOT AVAILABLE

AIR FORCE IN-HOUSE RESEARCH ON RAMJET COMBUSTORS

R. R. Craig, R. S. Boray, P. L. Buckley, D. L. Davis, K. G. Schwartzkopf
and F. D. Stull

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Dump combustors (co-axial or side entry) have become the basis for modern volume limited ramjet missile designs. Since the combustor must generally contain the rocket boost propellant in an integral rocket/ramjet design, use of conventional can combustors is not permitted. Flame stabilization depends largely on the recirculation zone formed by the sudden area change at the inlet duct, combustor junction. Additionally, if required, flameholders may be placed in the inlet duct resulting in a substantial, additional pressure loss. Although many such combustors have been successfully fabricated and tested over the past several years, the specific nature of these prior designs have precluded obtaining a sound technical data base or detailed flowfield data necessary for combustor modeling efforts. The objective of the in-house research programs being conducted by the Ramjet Engine Division of the Aero Propulsion Laboratory is to provide such a data base for the development of compact ramjet combustors having wide ignition limits, high combustion efficiencies and low total pressure losses over a wide range of flight conditions, and to provide detailed data for combustion modeling studies.

Our most recent efforts have been concerned with the practical application of swirl to the co-axial dump combustor. A design procedure was developed to simply replace flameholders with fixed, contoured vane swirlers having various design swirl numbers and various swirl velocity profiles. Design swirl number was varied from 0.3 to 0.5 and four different swirl velocity profiles were tested. The majority of the testing has been conducted in 6" diameter combustors. High combustion efficiencies, with combustor L/D's of 1.5, are easily obtained as fuel air-ratios approach stoichiometric. At low fuel-air ratios, judicious placement of the fuel injectors is required to obtain good efficiencies. Tests with 12" diameter combustors indicate that comparable results can be obtained in large scale, but that placement of the fuel injectors does not scale. Pressure losses with the swirlers are substantially less than losses with comparable high-blockage flameholders.

Combustion instability studies have documented the frequency and magnitude of pressure oscillations in various configurations of 6" diameter dump combustors with flameholders, without flameholders and with swirl. A short test program was also conducted to determine the effects of a simulated diffuser shock train, upstream of the combustor inlet, on combustor instabilities. High frequency oscillations tended to be somewhat amplified while low frequency oscillations tended to be damped when using wall mounted tube-type orifice fuel injectors. With uniform fuel-air mixtures, there was no definitive trend.

Models of the ducted rocket dual-inlet, side-dump combustor have been fabricated and installed in our water tunnel facility for flow visualization studies and in our cold-flow, blow-down facility for probing and gas sampling studies. (The water tunnel testing to date has been mainly limited to motion picture recording of the flowfield. The blow-down facility operation has been severely hampered due to facility computer failure and its subsequent replacement.)

Continued laser doppler velocimeter (LDV) measurements in a co-axial dump combustor model have definitively established the need for correcting LDV data in highly turbulent flows for velocity biasing errors. Modifications to the test model to insure uniform seeding of the flow, yielded velocity profiles which when integrated to yield mass flow rates, produced values 20% greater than measured mass flow rates. The magnitude of the error depended on the turbulence intensities at the station being profiled. Modifications to the counter processor to correct for this biasing have been completed, but validation of the correction procedure awaits additional interfacing with our computer data acquisition.

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2. Stull, F. D., Craig, R. R., Boray, R. S., "A Summary of Air Force In-House Ramjet Combustor Research and Development," 17th JANNAF Combustion Meeting, CPIA Publication 329, November 1980.

3. Boray, R. S., Chang, C., "Flowfield Studies of Ducted Rockets," 17th JANNAF Combustion Meeting.

4. Boray, R. S., Phelps, J., Viets, H., "Variable Geometry Nozzles for Dump Combustors," 17th JANNAF Combustion Meeting.

5. Boray, R. S., Chang, C., "Flowfield Studies of Dump Combustors," AIAA 5th International Air Breathing Symposium, Bangalore, India, February 1981.

APL IN-HOUSE AND SUPPORTED RESEARCH, DEVELOPMENT NEEDS IN TURBO PROPULSION COMBUSTION TECHNOLOGY

J. Petty
Aero Propulsion Laboratory
Wright Aeronautical Laboratories (AFWAL)

ABSTRACT NOT AVAILABLE

AFRPL IN-HOUSE AND SUPPORTED RESEARCH AND NEEDS ASSOCIATED WITH MULTIPHASE CHEMICALLY REACTING FLOW SYSTEMS

D. Mann
Edwards AFB, Ca
AF Rocket Propulsion Laboratory

<u>ABSTRACT NOT AVAILABLE</u>

Tuesday AM Session

8:30 Morning Chairman

J. Petty
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

8:35 Injection, Atomization, Ignition and Combustion of Liquid and Multiphase Fuels in High-Speed Air Streams

J. Schetz
VPI and State University

9:00 Turbulent Mixing and Combustion in High Speed Flows

C.Peters & R. Rhodes
AEDC/ARO

9:25 Fundamental Modeling of 3-Dimensional Multiphase Reacting Flow Systems

J. Swithenbank
Sheffield University, England

9:50 Fundamental Studies of Chemical Reactions in High Speed Turbulent Flows

H. Liepmann, Rosko and Dimotakis
California Institute of Technology

10:15 BREAK

10:30 Mixing, Ignition and Combustion in Flowing Reacting Fuel-Air Mixtures

R.B. Edelman & P.T. Harsha
Sciences Applications Inc.

10:55 Turbulent Mixing and Combustion of Multi-Phase Reacting Flows in Ramjet and Ducted Rocket Environments

K. Schadow
Naval Weapons Center

11:20 Fundamental Studies of High Energy - High Density Fuel Ignition and Combustion in Ramjet and Ducted Rocket Environments

M. King
Atlantic Research Corporation

11:55 LUNCH

INJECTION, ATOMIZATION, IGNITION AND COMBUSTION OF LIQUID FUELS IN HIGH-SPEED AIR STREAMS

Joseph A. Schetz and A. K. Jakubowski

Aerospace and Ocean Engineering Department
Virginia Polytechnic Institute and State University

Transverse injection of liquid and/or liquid-slurry jets into high speed airstreams finds application in several propulsion-related systems. For supersonic flows, these include thrust vector control and external burning for projectiles as well as scramjet engines, and for subsonic airstreams, "dump" combustors and afterburners, in addition to ramjets. All include physical processes associated with gross penetration, jet breakup and atomization, and, some chemical processes. Current work at Virginia Tech concentrates on three aspects of the complex physical processes - effects of injectant physical properties on breakup and atomization, breakup and atomization of impinging jets and the breakup of slurry jets.

The research is conducted primarily in the Virginia Tech 23 cm. X 23 cm. Transonic/Supersonic Wind Tunnel at $0.4 < M < 4.0$ with $T_0 = 300°K$ and $1.5 < P_0 < 10$ atm. The instrumentation used is mainly optical involving high-speed motion pictures (up to 45,000 pic/sec.), short-duration photomicrographs (10^{-8} sec.), a rotating mirror camera to obtain two to four frames at a framing rate of 10^5 pic/sec. and a laser for diffractively scattered light droplet size measurements.

A study of the transverse injection of particle-laden liquid jets into a Mach 3.0 air stream was conducted. Silicon dioxide particles having an average diameter of 5 microns were suspended in water and injected at particle loadings of up to 50%. Streak and nanoflash photographs were taken to study the particle-liquid interactions and the penetration of the jet. The particles were found to agglomerate and separate from the liquid portion of the jet. Neither the penetration nor the break up of the liquid portion of the jet were significantly effected by the addition of the particles.

A study was undertaken to determine the feasibility of utilizing jet impingment to enhance atomization in a crossflow situation. Two angled jets impinged such that the resultant jet issued perpendicularly into a supersonic airstream. The plume was carefully examined to determine penetration and the droplet size distribution. Identical tests were performed with a circular injector of equivalent area to determine the relative success of the method. The results showed that a significant reduction in droplet diameters was achieved by the impinging technique. The alignment of the impinging jets relative to the freestream was also found to be a factor in the degree of atomization.

The characteristics of a liquid jet injected into a supersonic crossflow as influenced by physical properties were studied. First, the effects on penetration of the jet were studied. Second, the dependence of the atomization process was investigated. The injectants were water and water solutions with glycerine and alcohol. The penetration of the plume was only slightly dependent upon physical property variations. The details of the break-up and atomization processes were strongly effected. The development and shape of the waves leading to jet column fracture changes. The detail of the atomization process from jet column to clumps to ligaments to droplets are modified by changes in physical properties.

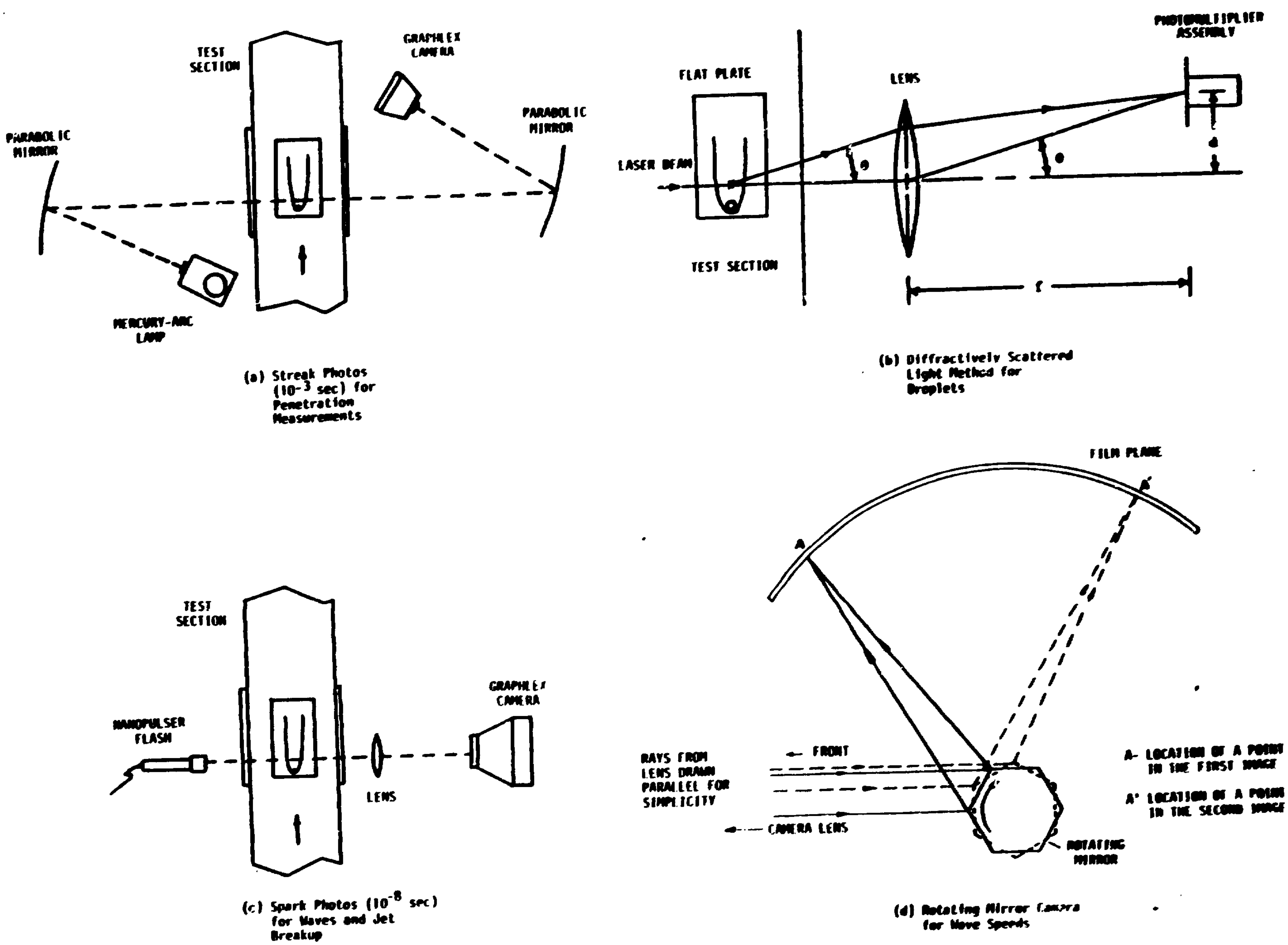


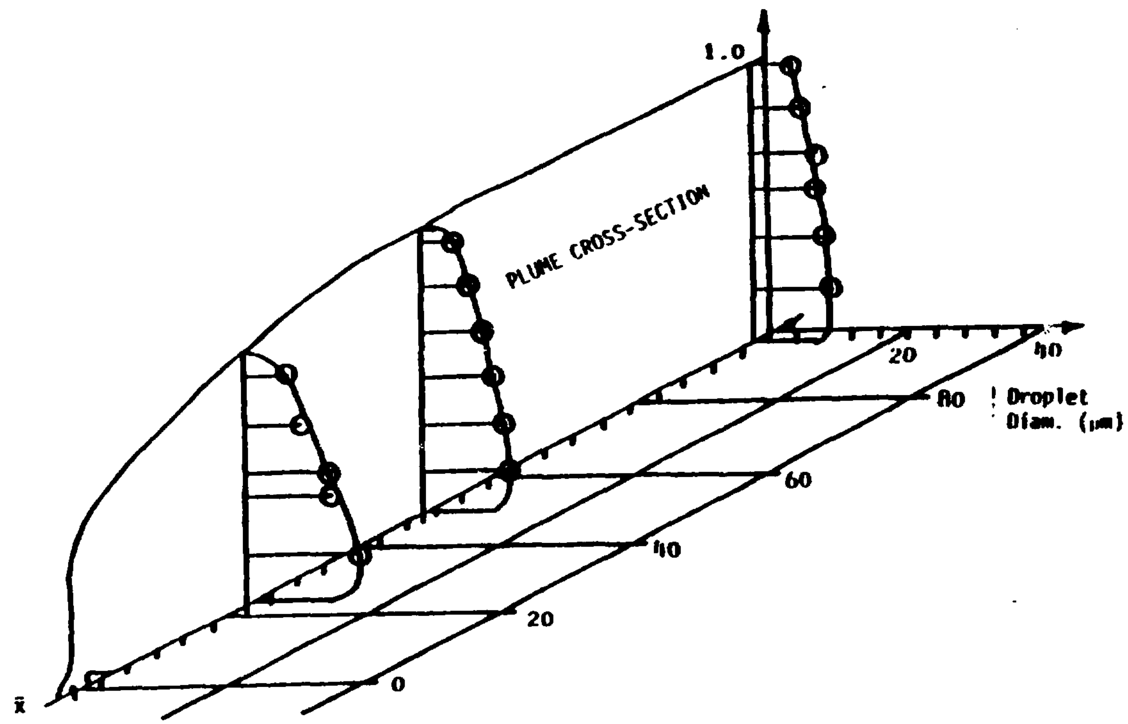
Figure 1 - Schematics of Some of the Optical Techniques Used at Virginia Tech.

Impinging Jets Aligned

x/d_j	y/h	D(μm)
10	9	15.1
15	10	15.1
25	4	15.2
25	10	12.1
25	12	12.5
25	16	8.6
25	20	6.2
50	4	12.9
50	8	11.7
50	12	10.0
50	16	7.8
50	20	6.5
50	24	6.5
95	5	11.5
95	9	10.5
95	13	8.8
95	17	10.0
95	21	7.9
95	25	6.5

Circular Jet

x/d_j	y/h	D(μm)
5	7	-
10	9	13.3
15	10	13.6
25	11	13.5
50	6	11.2
50	9	11.6
50	12	14.5
50	16	13.9
50	19	14.5
50	22	31.1
50	25	12.8
95	3	13.9
95	6	14.0
95	9	13.5
95	12	16.0
95	16	15.5
95	19	15.9
95	22	12.0
95	25	10.0



$\rho_j V_j^2/\rho_\infty V_\infty^2 = 12$

Figure 2 - Droplet Size Results for *Impinging-Jet Injector* Compared to a Single Circular Jet.

TURBULENT MIXING AND COMBUSTION IN HIGH SPEED FLOWS

C. Peters & R. Rhodes
AEDC - ARO Inc
Tullahoma, Tn
(AFOSR-PO-81-00003)

<u>ABSTRACT NOT AVAILABLE</u>

Fundamental Study of Three Dimensional Two Phase Flow in Combustion Systems

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Principal Investigator

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The long term objective of this research is to provide a rational, reliable and comprehensive design method for the various combustion systems (e.g. gas turbines and ramjets) of interest to USAF. This goal would result in quicker and cheaper development of more versatile and innovative systems incorporating greater efficiency and operating limits.

The approach has been to develop and extend previous finite difference computer algorithms to the required level for application to 3-dimensional two phase hot flows. This has been an ambitious task and requires the simultaneous solution of the strongly coupled equations describing fluid dynamics, chemical kinetics and evaporating droplets. Along side of this has been the application and development of suitable experimentation to enable the appropriate comparison with modelling predictions, and this aspect of the work has also sought to improve measurement accuracy and efficiency by the development of non-intrusive optical techniques which lend themselves to ease and speed of data collection and analysis.

As a first step, comparison between computed and measured 3-dimensional cold flow fields were made for a gas turbine can. This indicated a weakness in the mathematical models when large swirl was present and recent work has indicated that better agreement can be obtained by a suitable correction to the Richardson number for the turbulent viscosity. This development continues to be evaluated by comparison experiments using laser Doppler anemometry to measure strongly swirling test flows.
Good agreement between calculated and measured hot flow fields was then obtained and encouraged the development of two phase studies. The first of these indicated the impacting behaviour of some droplets on the combustor wall and when this was extended to incorporate droplet evaporation, the trajectory-size relationship indicated that this analysis provided the basis for choosing fuel nozzle types for combustor designs, particularly at off design operation.
Figure 1 indicates all the elements of the approach and the way in which they inter-relate and contribute to gas turbine analysis.

As part of the experimental back up, residence time measurements have also been made using 1.5 msec mercury vapour pulses which are detected optically at the combustor exit. This permits immediate residence time distribution observation and also provides a route to mixing theory validation by observation of the RTD variance as well as comparison with the RTD predicted by the statistical gas turbine flow algorithm.
Figure 2 demonstrates some representative computation results for two phase flow in a gas turbine based on the calculated cold flow field.

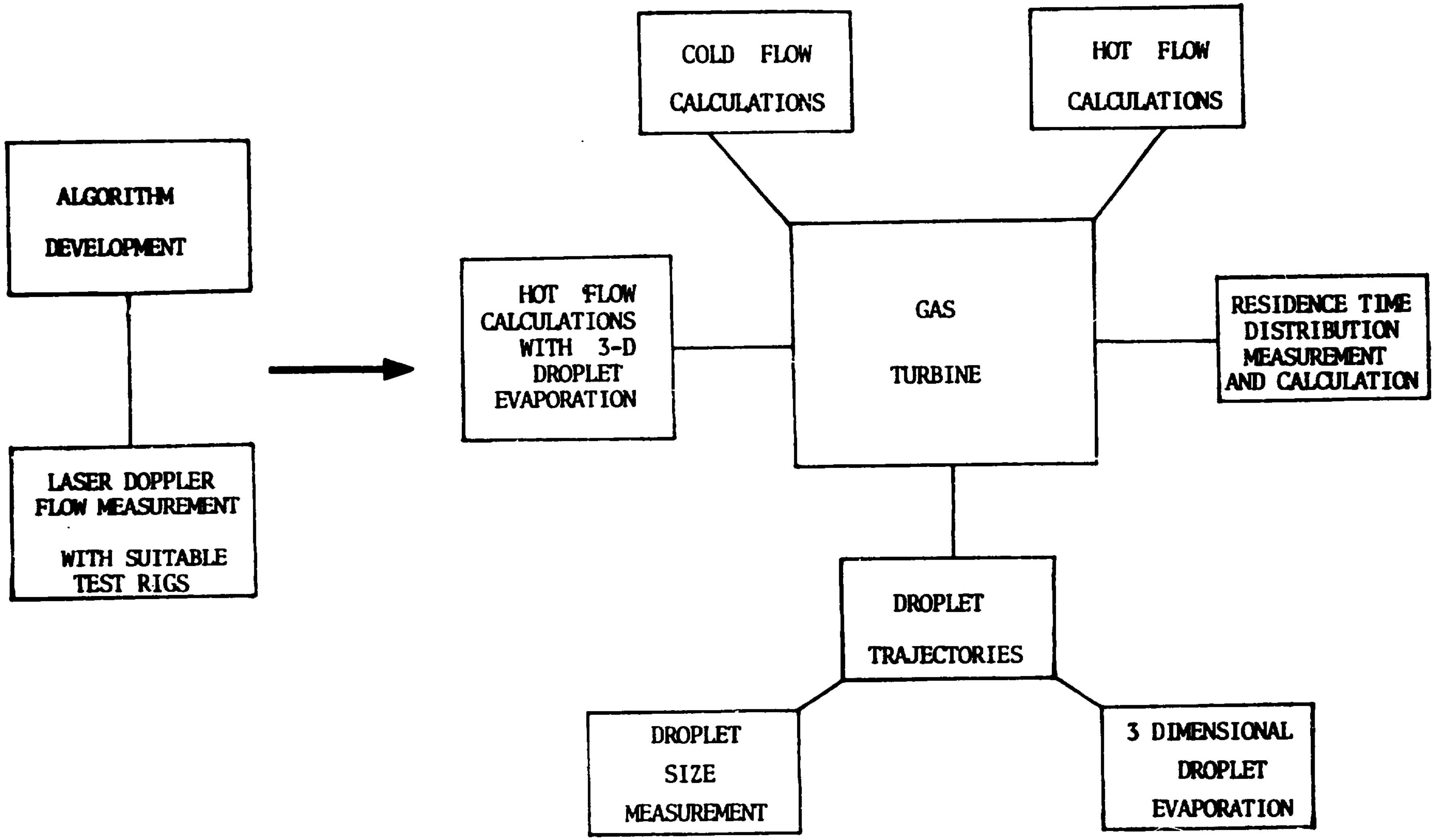


FIGURE 1 DEMONSTRATION OF THE ELEMENTS CONTRIBUTING TO THE PROGRAM AND THEIR INTER-RELATIONSHIP

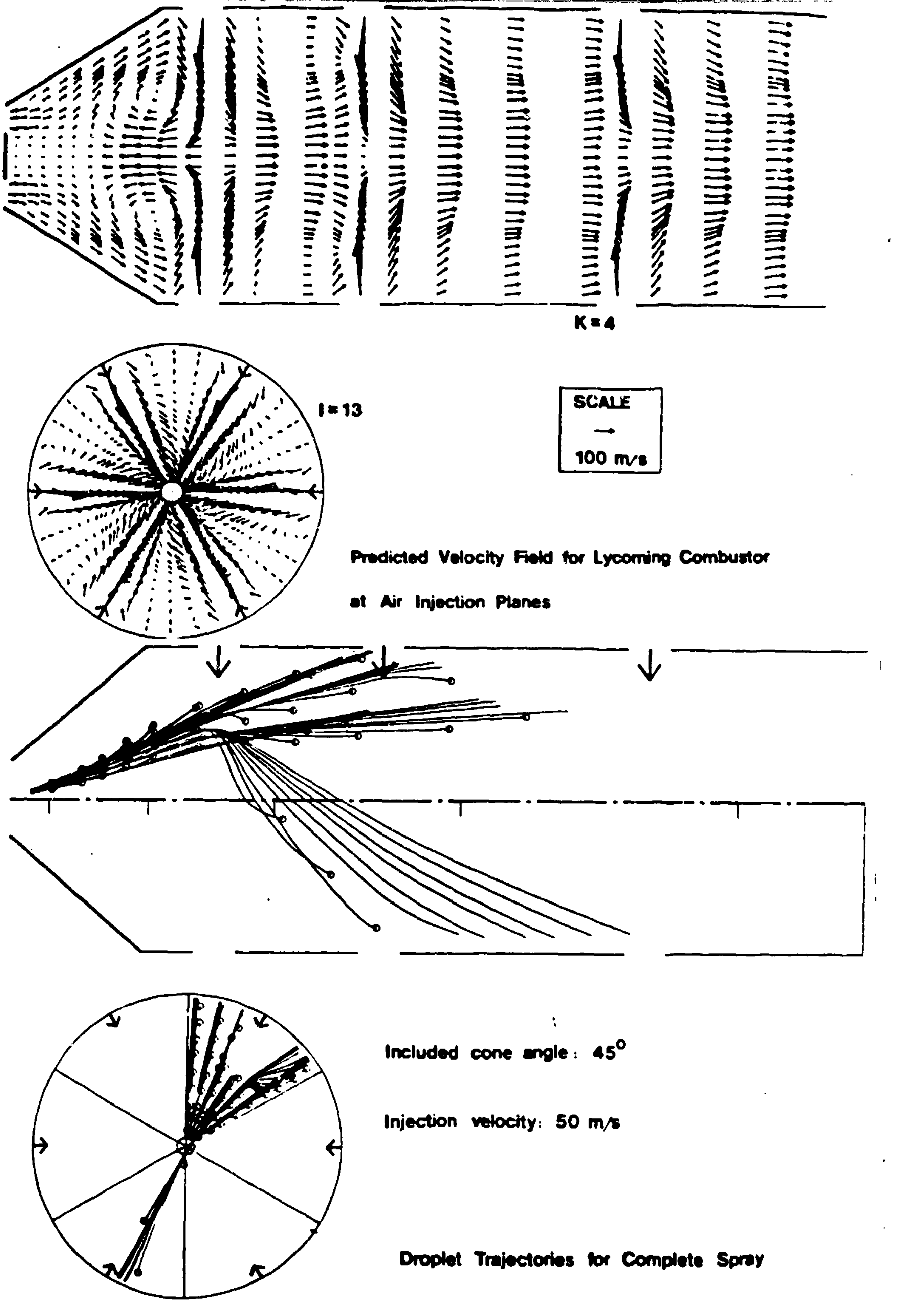
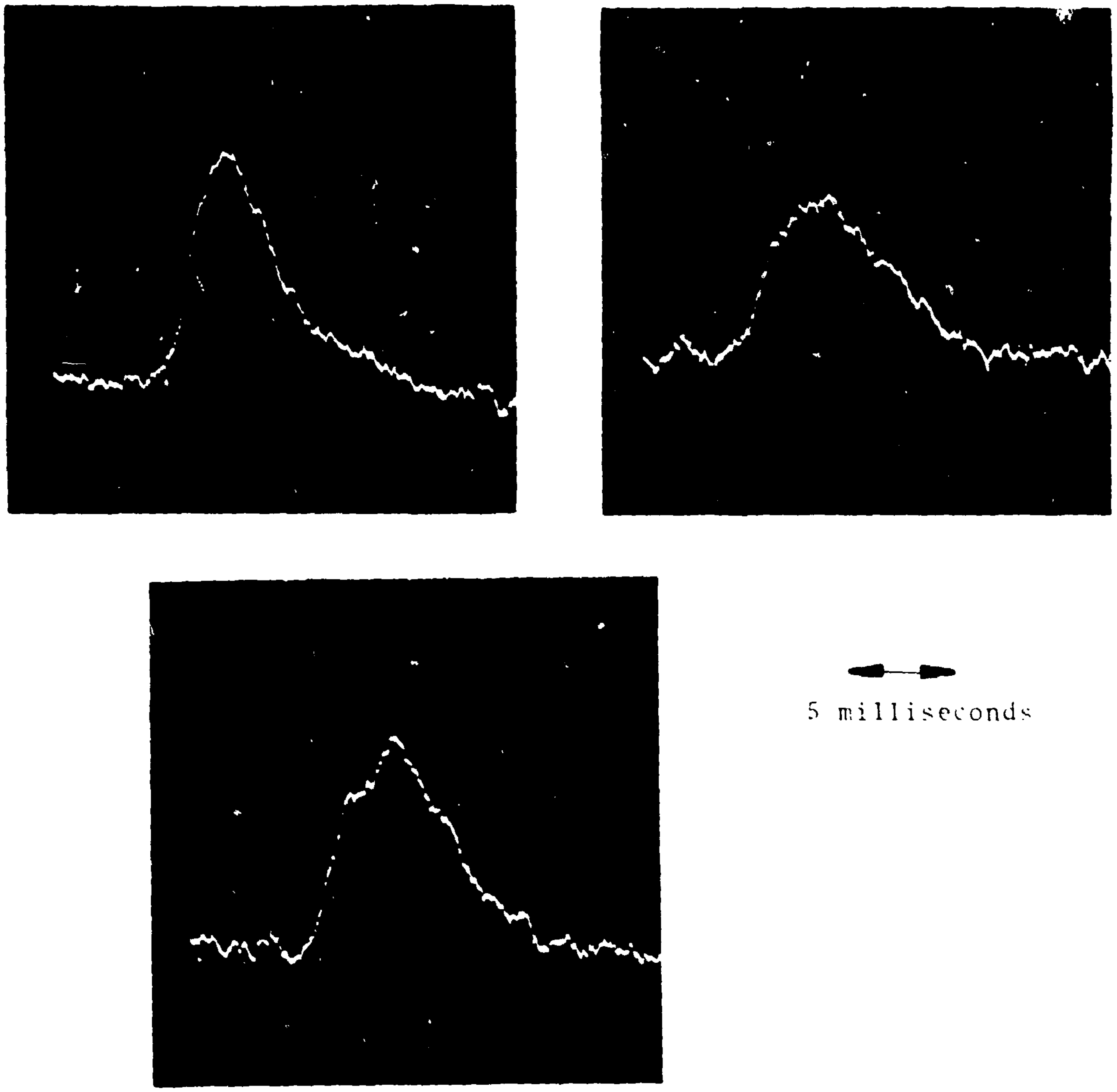
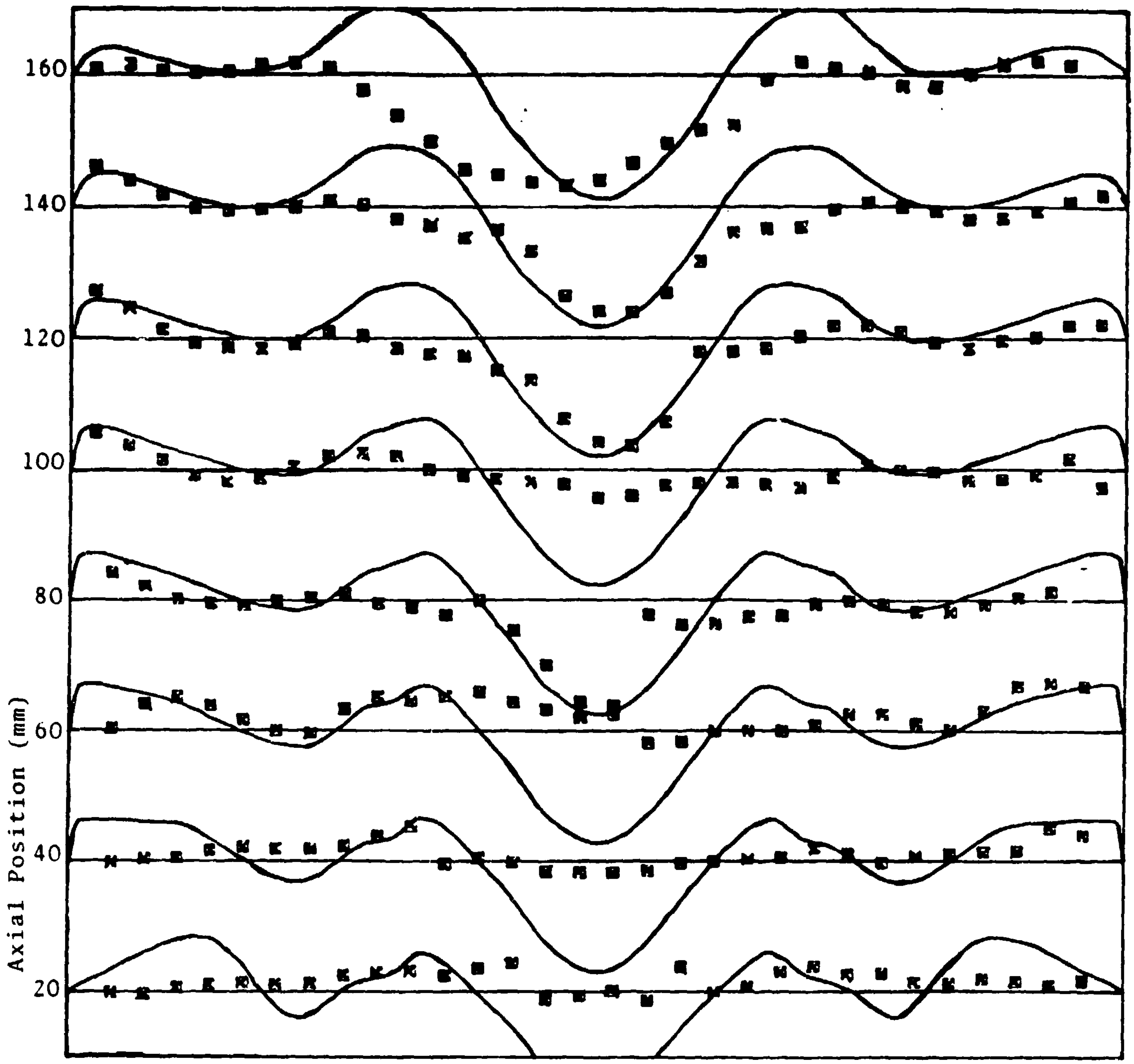


FIGURE 2 CALCULATION OF VELOCITY FIELD AND DROPLET TRAJECTORIES FOR LYCOMING COMBUSTOR

VU-GRAPH (1)

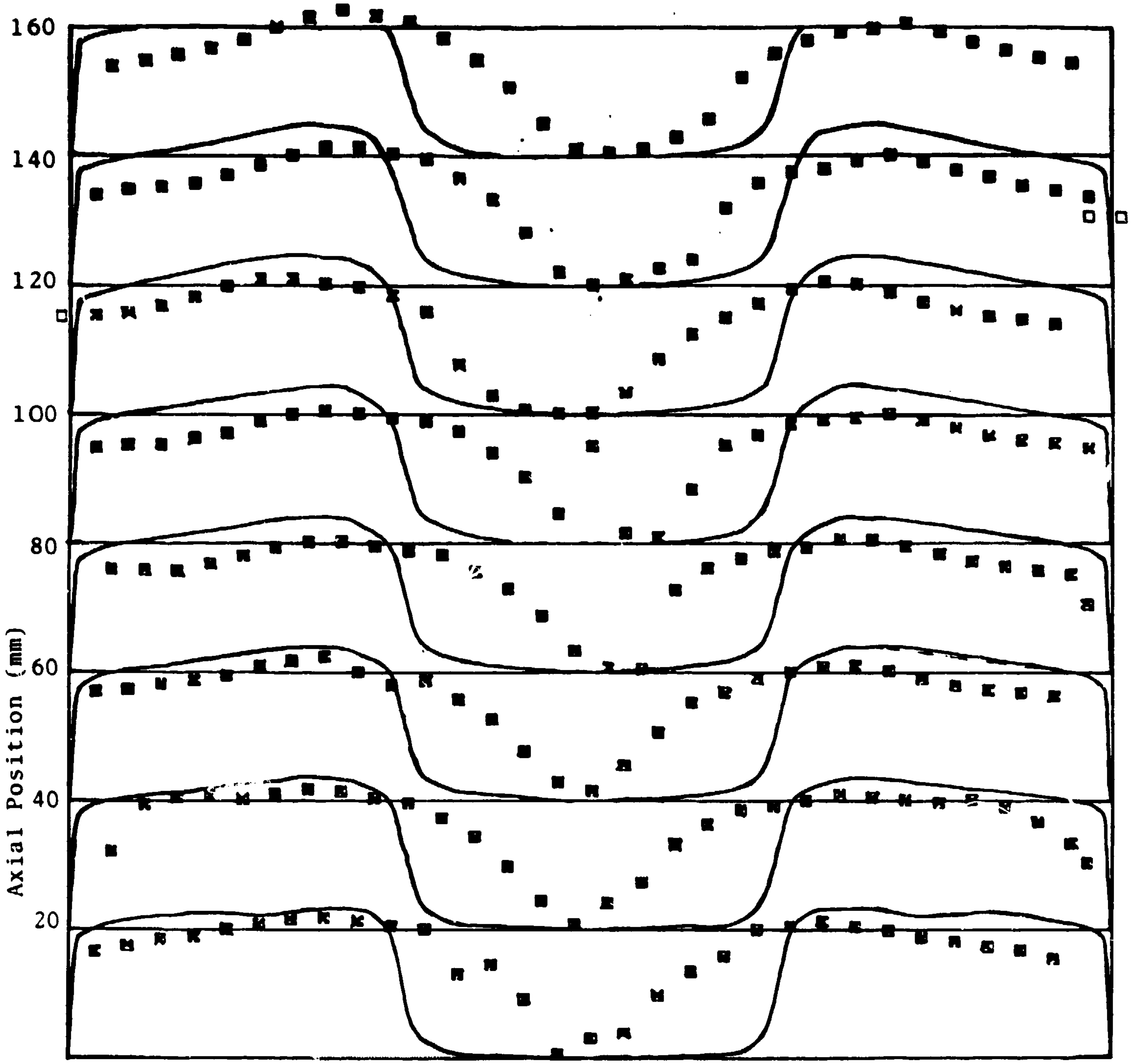


Example of pulse response signals obtained with mercury vapour pulse input. Pulse input is 1.5 msec long and begins at the beginning of the trace. These traces are effectively residence time distribution functions, whose slight variability arises through turbulence and random mixing processes and which may be investigated by means of the variance as a function of time.



As part of flow algorithm development, this represents a test of the Richardson number correction for the case of high swirl, and is the axial velocity profile versus diameter for a 20 cm diameter cyclone. Points are the measured values from laser Doppler anemometry and the continuous curves are the calculated functions. Velocities are normalised to the chamber maximum and axial stations are measured from the back plate.

VU-GRAPH (3)



Tangential velocity profile for the cyclone of Vu-Graph (2). Velocities are normalised to the chamber maximum and are reversed in sign for the right hand radial positions.

CHEMICAL REACTIONS in TURBULENT MIXING FLOWS

H. W. Liepmann, G. L. Brown, P. E. Dimotakis, A. Roshko

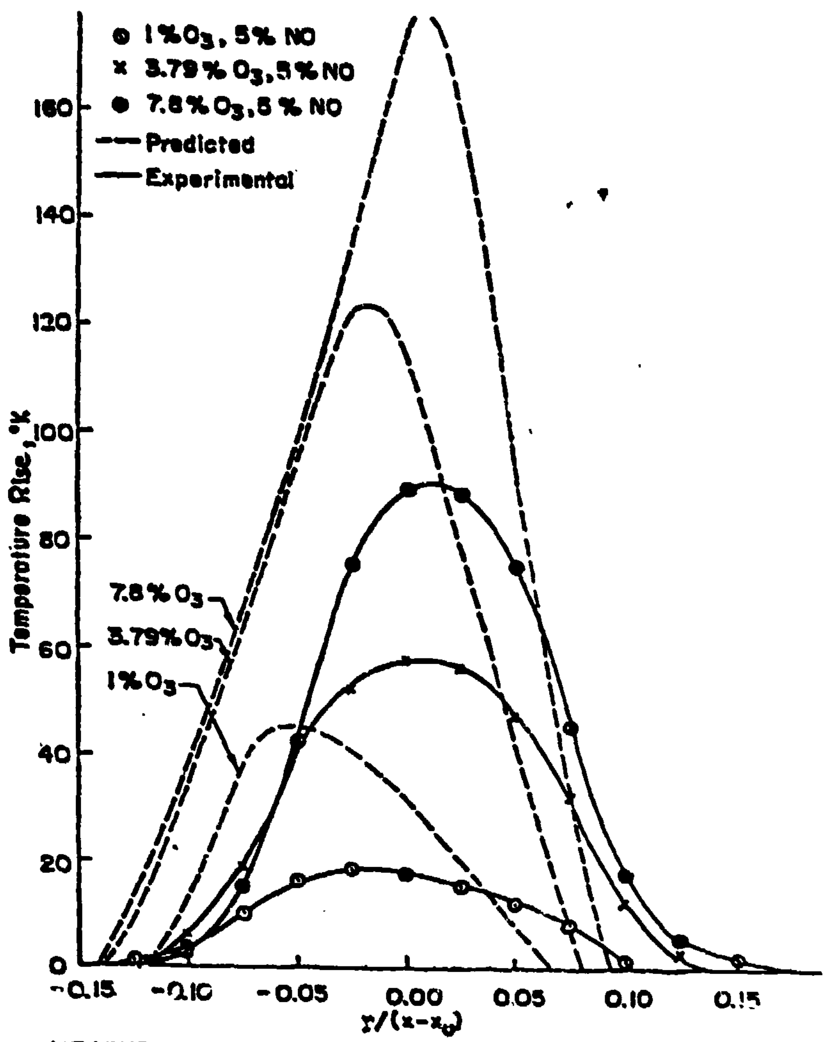
Graduate Aeronautical Laboratories
of the
California Institute of Technology

The purpose of this effort is to investigate the fundamental processes and phenomena of mixing limited chemical reactions of non-premixed reactants in a turbulent flow environment. Experiments to date have concentrated on two geometries (plane shear layer and round jet) in both gaseous environments and water. The effects of molecular diffusivity (Schmidt number; water vs. air), Reynolds number, equivalence ratio, and heat release are under investigation.

These investigations are complemented by efforts to develop simple analytical models, which have met with encouraging success to date in applications to chemically reacting shear flows with low accompanying heat release in reacting jets and shear layers.

A third part of this research effort has concentrated on the development of experimental techniques and instrumentation necessary for the experimental work. Such developments, completed or under way, include a multi-channel LDV system (to be used for short running time experiments), particle streak velocity field measurements, acoustic phased array velocity/temperature field mapping (for hostile environments), and a temperature probe array for high temperature and hostile environment (fluorine, hydrogen fluoride measurements. A new shear flow facility to burn hydrogen and fluorine at high Reynolds numbers and variable heat release has recently been completed.

Two examples of recent results under the present investigation are included in the following pages. The first (figure 1) compares experimental results and computational predictions of the temperature profiles in a reacting shear layer. The second (figure 2) is a photograph of the chemical product formed in the plane of symmetry of a chemically reacting jet. It should be noted that both sets of data strongly suggest that gradient diffusion models, used almost exclusively both analytically and computationally at present, yield results badly at variance with experiment.



MEASURED AND PREDICTED TEMPERATURE DISTRIBUTION IN SHEAR LAYERS BETWEEN NITRIC OXIDE AND OZONE

FIGURE 1

Combustion mean temperature profiles in a nitric oxide - ozone reacting shear layer. Effect of equivalence ratio (variable ozone concentration, fixed nitric oxide concentration). Experimental results in qualitative and quantitative disagreement with gradient diffusion computational model calculations. Models predict a shift of the peak temperature profile towards the leaner reactant, in contradiction with experimental results, and overestimate the peak temperatures (factor ~ 2).

FIGURE 2

Chemically reacting jet in water. Time resolved chemical product distribution in the plane of symmetry of the jet. Reynolds number ~ 10,000. Equivalence ratio 25 parts reservoir fluid needed to react with one part of jet fluid. Product made visible by means of Laser Induced Fluorescence. Note absence of any product for approximately 25 diameters and completion of jet fluid burn-up in roughly 75 diameters. These results are also in qualitative disagreement with any gradient diffusion models.

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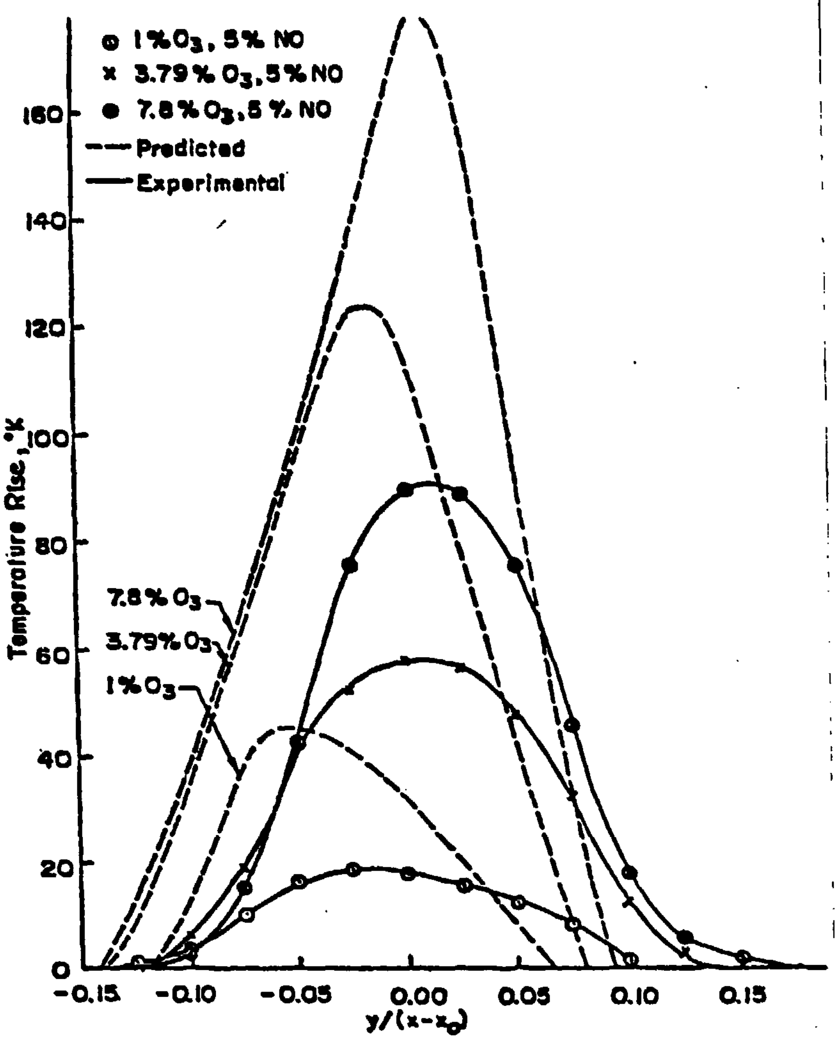

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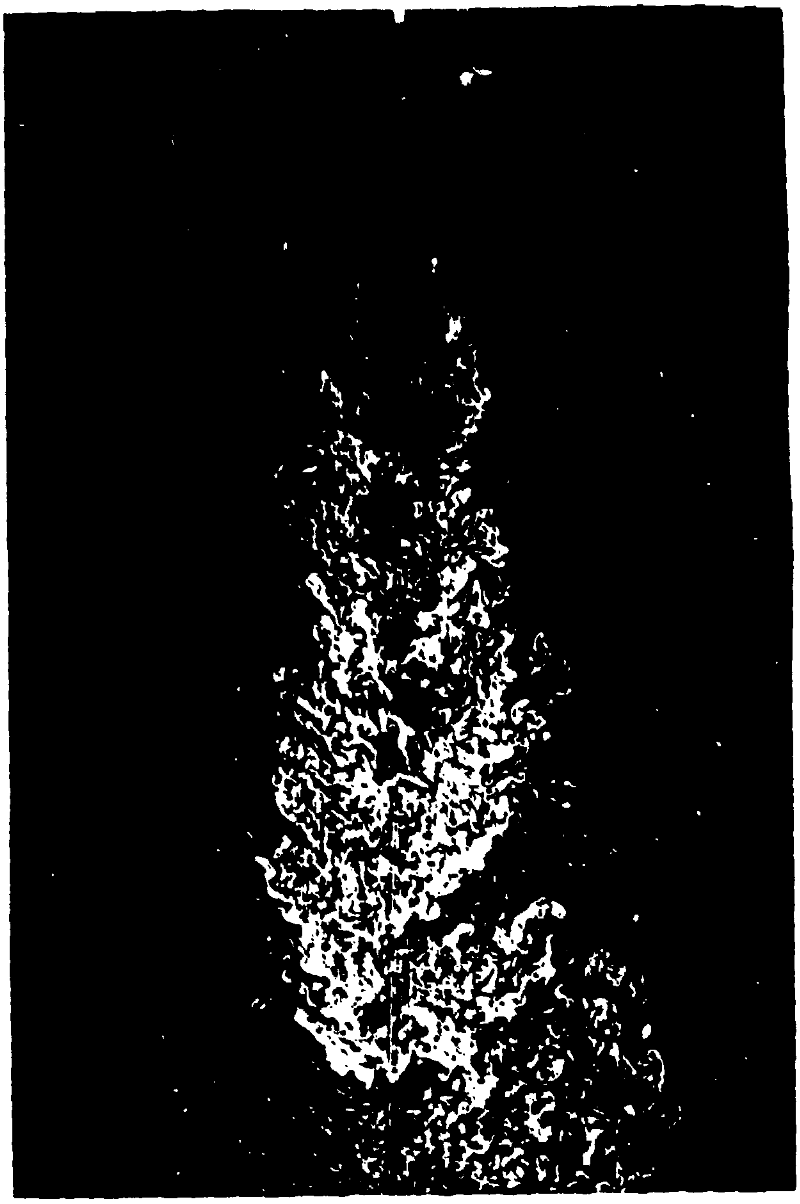

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COMBUSTION IN HIGH SPEED AIR FLOWS (F49620-80-C-0082)

Raymond B. Edelman and Philip T. Harsha

Science Applications, Inc.
Combustion Science and Advanced Technology Department
9760 Owensmouth Avenue
Chatsworth, CA 91311

The purpose of this research is the investigation of fundamental mechanisms involved in combustion in high-speed air flows through the development of realistic combustion and combustor models and comparison of the predictions of these models with experimental data. The modular combustor model has been a major focus of the research partly because it provides a means for incorporating detailed analytical treatments of each of the processes occurring in high-speed combustion and, most importantly, the coupling between these processes. Liquid- and slurry-fueled combustion processes are being investigated for both axisymmetric sudden expansion ramjet combustors and three-dimensional ducted rocket configuration.

Characteristics of the modular model approach are outlined in Figure 1. The basic concept involves the subdivision of the combustor flowfield into characteristic regions which, for the axisymmetric sudden-expansion configuration include the large-scale recirculation region, the nonrecirculating viscous main flow, and the shear layer which both separates and provides the coupling between the other two regions. Each of these regions is computed in detail using appropriate modeling, allowing the detailed analysis of key processes such as turbulent mixing, chemical kinetics, fuel injection, spray formation, vaporization, and mixing, and heterogeneous mixing processes involving both droplets and particles as appropriate for slurry fuels. Although shown for the axisymmetric sudden expansion, the modular model concept is extendible to more complex geometries, such as the three-dimensional ducted rocket configuration. It should be noted that the use of the model requires an aerodynamic characterization of the flowfield: this can be obtained from experimental data or through use of an elliptic aerodynamic model depending on available experimental data.

One key result obtained through use of the modular model for a liquid-fueled sudden expansion combustor is outlined in Figure 2. Flame propagation processes in such a combustor are critically dependent on the chemical state of flow in the recirculation region, which is in turn dependent on the entrainment of fuel into the recirculation region. This entrainment process is *predicted* by the SAI modular model (i.e., it is not assumed *a priori* as in other modular approaches). As the upper curve shows, the model predictions are in good agreement with correlations obtained from experimental data, both with respect to level and to the trend observed in experiments between cold flow and reacting flow data obtained in the same configuration. The entrainment rate of the *fuel* depends on the distribution of fuel in the main flow external to the recirculation zone, and this in turn depends on the penetration of liquid fuel into the inlet airstream. This dependence is one of the factors that has defeated attempts to correlate stability data for sudden expansion combustors based on global equivalence ratio.

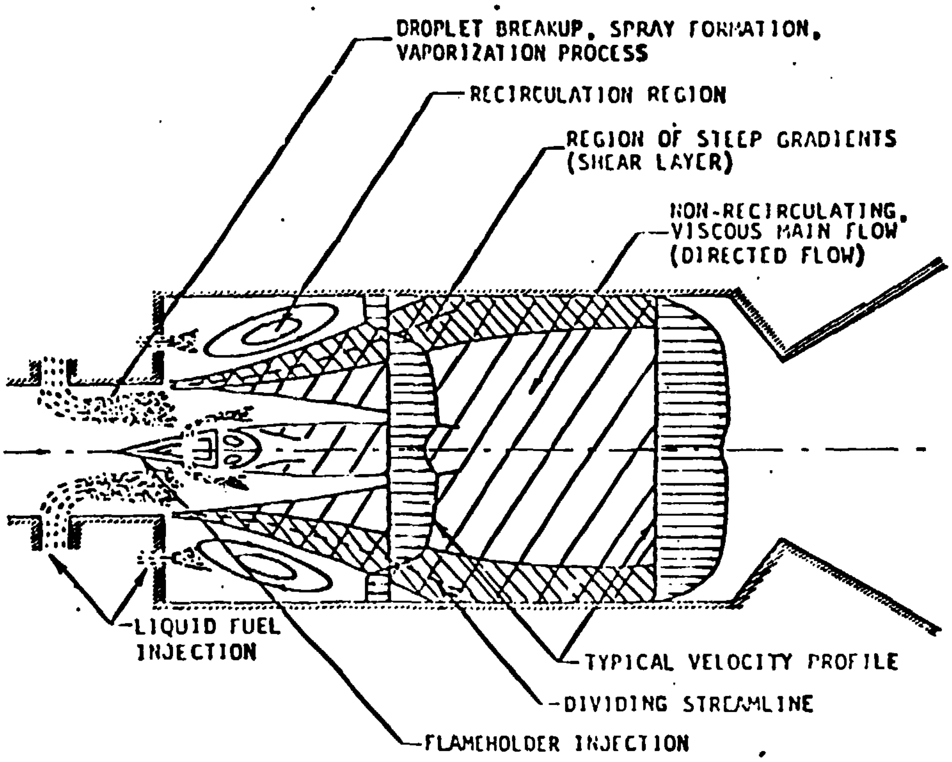
The lower curve on Figure 2 shows that computed dependence of the recirculation zone equivalence ratio on fuel penetration height for an overall (global) equivalence ratio of 1.0. As noted in Figure 2, for low values of penetration the recirculation region can become highly fuel-rich, with a consequent reduction in temperature (as well as completeness of combustion) leading to low overall combustor performance. These results were utilized to interpret recent ramjet combustor test data: configuration changes designed to increase the fuel jet penetration led to improved overall performance as predicted by the model. This provides an example of the type of output that is a fundamental overall goal of this program: to provide, through the use of realistic and detailed modeling, the understanding of the fundamental mechanisms involved in combustion necessary to improve and optimize overall combustor performance.

TECHNICAL APPROACH

Science Applications, Inc. — P. I. Raymond B. Edelman

Combustion In High Speed Air Flows — P. T. Harsha

- Modular Combustor Model



- Detailed Treatments for Characteristic Flowfield Regions
    - •• Recirculation zone
    - •• Main (directed) flow
    - •• Shear layer

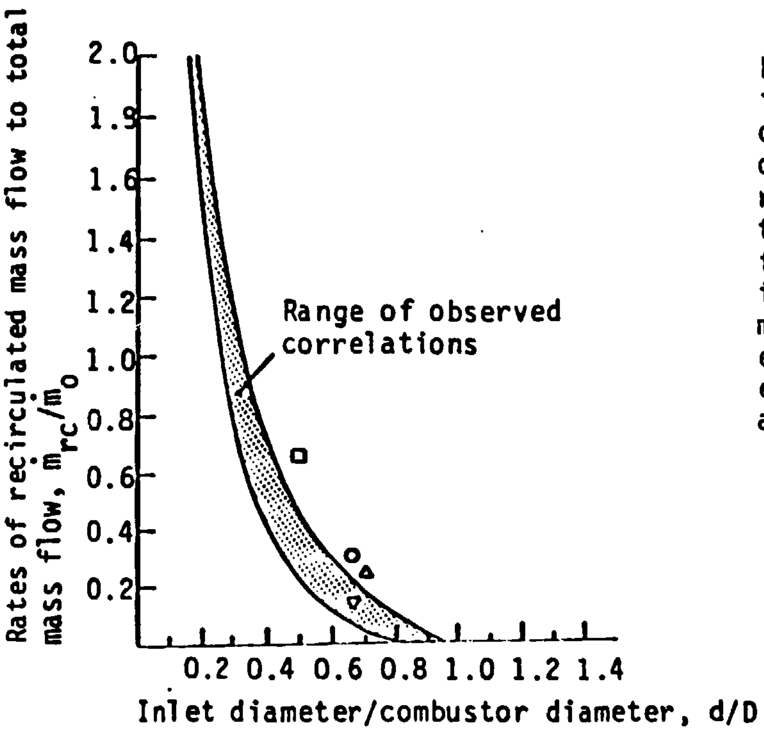
- Detailed Models of Key Processes
    - •• Turbulent mixing
    - •• Chemical kinetics
    - •• Fuel injection
    - •• Spray
    - •• Heterogeneous flow (slurries)

- Extendable to 3-D Flows
    - •• Ducted rocket

FIGURE 1

Science Applications, Inc.
P. I. Raymond B. Edelman
P. T. Harsha

Combustion In High Speed Air Flows



Flame stabilization/propagation processes in sudden expansion combustors are critically dependent on the state of chemical kinetics mechanisms in the recirculation region. This state in turn depends on entrainment of fuel and air from the main flow into the recirculation region. The modular model accurately predicts this entrainment process, and predicts effects on entrainment of reacting flow as compared to cold flow.

Modular Model Predictions

○ compressible cold flow
□ incompressible cold flow
▽ reacting flow, T_i = 535 K
△ reacting flow, T_i = 1600 K

Low performance of sudden expansion combustors under some conditions can be explained by the interaction between fuel penetration and the amount of fuel entrained into the recirculation region. For low penetration heights, (wall fuel injection) the equivalence ratio in the recirculation region can be extremely fuel-rich, i.e., ϕ_{RZ}=4.5. This results in low recirculation region temperatures, poor flame propagation, and overall low combustor performance. Experiments have confirmed the predicted trends.

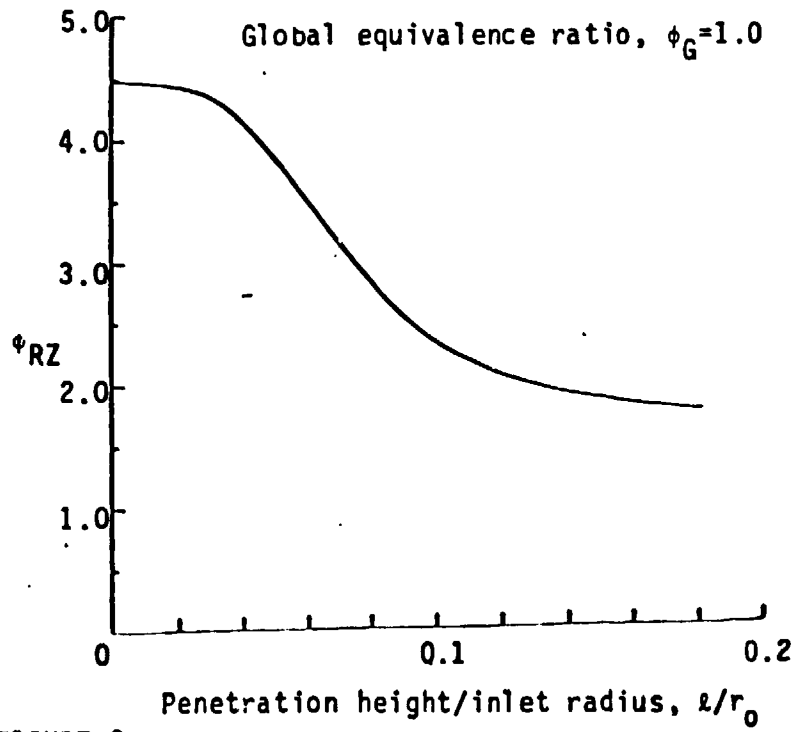


FIGURE 2

TURBULENT MIXING AND COMBUSTION OF MULTI-PHASE REACTING FLOWS IN RAMJET AND DUCTED ROCKET ENVIRONMENTS

Klaus C. Schadow

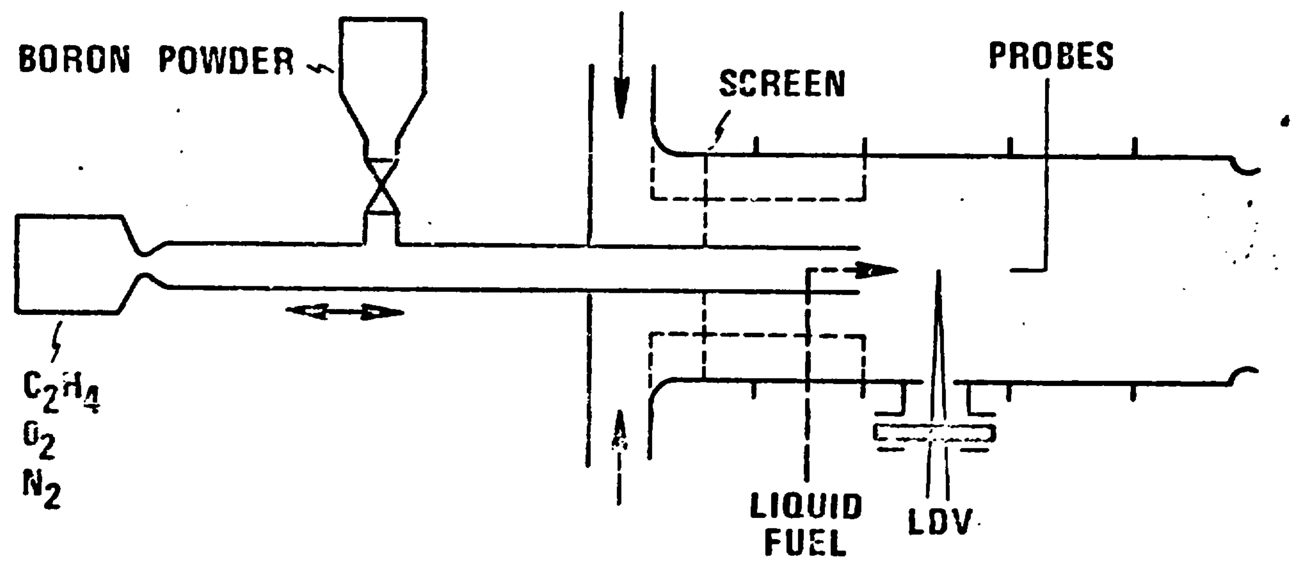
Naval Weapons Center
China Lake, California

Turbulent mixing and combustion of multi-phase flows are relevant to problems in many airbreathing propulsion systems, such as the gas generator ramjet (ducted rocket) with solid boron propellants and the slurry fuel ramjet. The ability to deal with the complex flow field in these systems requires detailed experimental and analytical knowledge of a number of coupled physical and chemical processes, including turbulent mixing, recirculating flow, and gaseous/particulate fuel ignition/combustion.

In recent years, considerable progress has been made towards development of analytical models to deal with the multitude of couple mechanisms, however, evaluation of the models has been hampered by the lack of detailed experimental flow-field information. The objective of this program is to obtain such experimental data that would specifically aid evaluation and further refinement of analytical techniques developed by Sciences Applications Inc. (Edelman and Harsha) under AFOSR funding. Because of the complexity of the phenomena to be studied, a systematic step-by-step approach will be taken for both the fuel characteristics (gaseous fuels, boron-laden gaseous fuels, liquid fuels, and slurry fuels) and the flow field (axisymmetric-coaxial, axisymmetric with dump, axisymmetric-noncoaxial, and three-dimensional). In the reporting period (six months), assembly and check-out of the laboratory combustor, including gaseous fuel gas generator, boron particle feed system, and ramjet combustor, were completed. Intrusive probes for species concentration and temperature (beryllium and yittrium oxide coated thermocouples) measurements were prepared. The three-beam, two-color Laser Doppler Velocimeter (LDV) for velocity and turbulence measurements with the support hardware (optical access to the flow field, cyclone particle seeding device) and computer software was made operational. Tests relevant to gas generator ramjet with coaxial mixing were started. Ignition and flame characteristics in the ramjet combustor were studied as function varying operational conditions in the gas generator (temperature, exhaust velocity) and ramjet combustor (turbulence intensity of air flow, pressure, equivalence ratio). Based on these results, test conditions were selected with SAI at which detailed flow meaurements will be performed. These experiments were started and the first test results will be presented at the meeting.

TURBULENT MIXING AND COMBUSTION OF MULTIPHASE FLOWS

- APPROACH
  - AXISYMMETRIC, 5-INCH DIAMETER LABORATORY COMBUSTOR TESTS WILL BE PERFORMED.
  - FUEL CHARACTERISTICS WILL BE VARIED FROM GASEOUS FUELS (BASELINE) TO BORON PARTICLE-LADEN GASEOUS FUELS, LIQUID FUELS AND SLURRY FUELS.
  - FLOW FIELD CHARACTERISTICS WILL BE VARIED FROM COAXIAL MIXING TO COAXIAL MIXING WITH DUMP AND NON-COAXIAL MIXING WITH CIRCUMFERENTIAL SLOT (AXISYMMETRIC), AND WITH AIR MULTI-INLETS (3 DIMENSIONAL).
  - MEASUREMENTS WILL BE MADE WITH INTRUSIVE PROBES AND NON-INTERFERENCE OPTICAL DIAGNOSTIC TECHNIQUES.



TURBULENT MIXING AND COMBUSTION OF MULTIPHASE FLOWS

- ACCOMPLISHMENTS
  - COMBUSTOR BUILT AND CHECKED OUT
  - LDV (3 BEAMS) OPERATIONAL
  - INTRUSIVE PROBES (GAS SAMPLING, COATED THERMOCOUPLES) PREPARED FOR TESTING
  - IGNITION (FLAME) CHARACTERISTICS FOR GASEOUS FUELS AND PARTICLE–LADEN GASEOUS FUELS DETERMINED FOR VARYING GAS GENERATOR (T, v) AND RAMJET COMBUSTOR (Φ, p) OPERATIONAL CONDITIONS
  - OPERATIONAL CONDITIONS FOR DETAILED FLOW MEASUREMENTS SELECTED WITH SAI (MODELING) AND EXPERIMENT STARTED

FUEL-RICH SOLID PROPELLANT BORON COMBUSTION

Merrill King, James Komar, Ronald Fry

Atlantic Research Corporation
Alexandria, Virginia

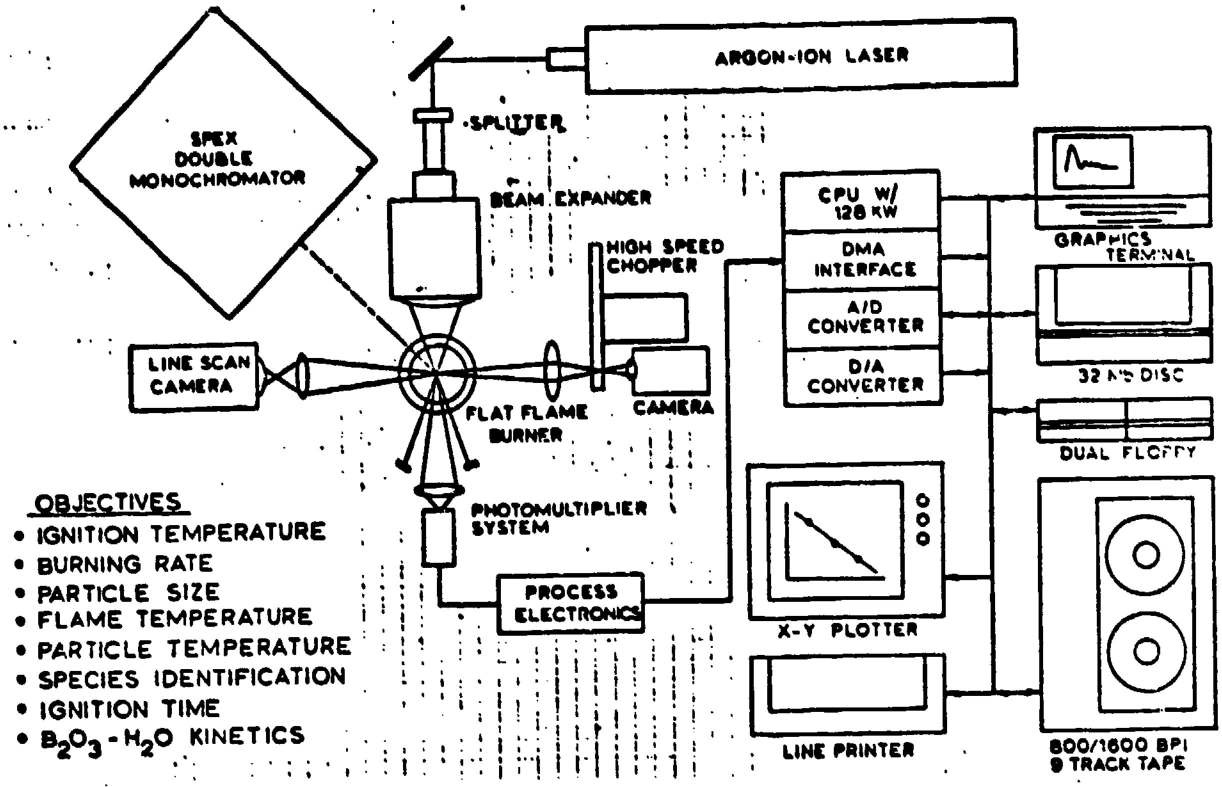
Boron is a particularly attractive ingredient for airbreathing missile fuels due to its high gravimetric and volumetric heating values. For achievement of full potential, however, boron particles must ignite and burn completely within a very limited residence time. Since boron particles are generally initially coated with an oxide layer which inhibits combustion and since boron metal has an extremely high boiling point which necessitates surface burning subsequent to oxide removal, this can become difficult, and afterburning efficiency problems have been encountered with boron fuels. Ramburner combustor design optimization is particularly critical to achievement of high efficiency and definition of approaches to such optimization depends on good understanding of the phenomena involved in boron particle ignition and combustion. A thorough critical review of the literature in this area has revealed numerous knowledge gaps.

A multi-faceted effort involving interlocked analytical and experimental tasks is planned. A list of the major tasks appears on Page 3. Fundamental experiments aimed at quantifying kinetics of various reactions involved in boron ignition and combustion will provide data to be used in detailed models of these processes. These models will in turn be combined with mass, momentum, and energy balance equations to develop prediction procedures for ignition and flame stabilization of boron dust clouds in combustors and for prediction of fractional heat release in confined volumes. Additional experiments will be conducted to confirm these predictive tools. In addition, various chemical and physical techniques aimed at improving boron ignition and combustion processes will be tested. Finally, flame structures associated with consolidated boron grains will be examined and means of tailoring these structures to desired characteristics will be investigated.

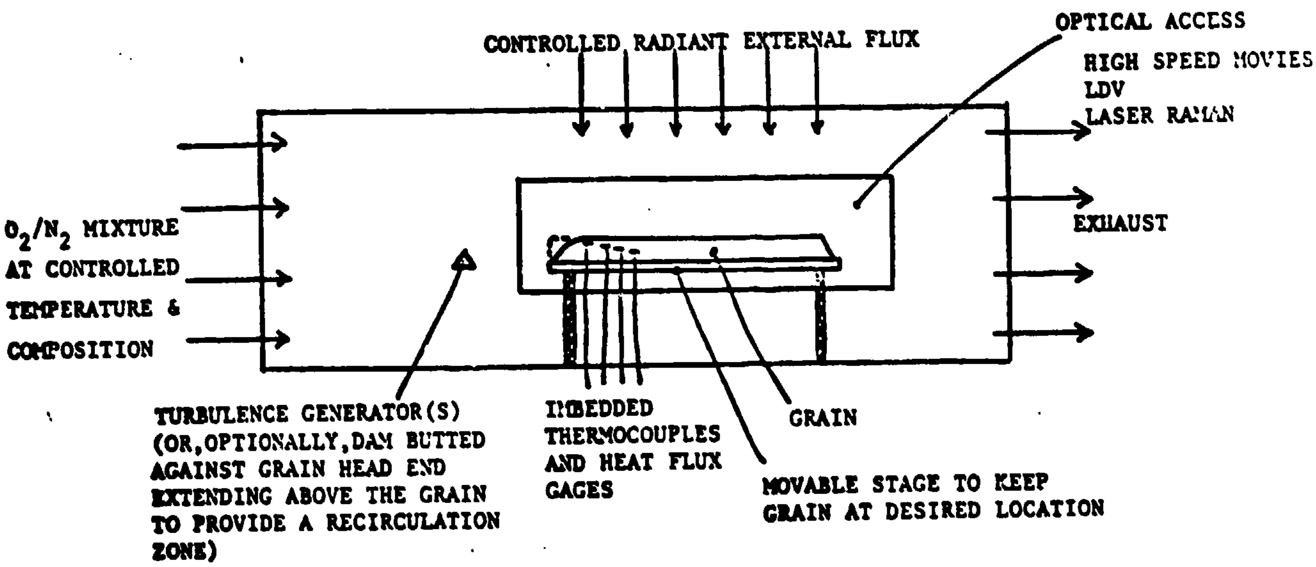
At this point, the literature review has been completed. In addition, major modifications to the equation set used in analyzing boron single particle ignition have been made, with use of information obtained from the literature (particularly the Russian literature) and a revised computer code for prediction of critical ignition conditions and ignition delay times is essentially complete.

A completely revamped, highly modernized (particularly in terms of data acquisition) flat-flame burner facility (Page 2 - Top) has been constructed and experimental studies of single particle ignition and combustion are just beginning. Diagnostic methods include conventional chopped-frame photography, line scan image intensification, laser velocimetry and particle interferometry. Spectral observations of the oxide coating degradation are planned for the near future.

The mechanisms involved in the ablation of consolidated boron grains in a high temperature air crossflow and in subsequent combustion of material leaving the surface are not well understood. (In fact, even the nature of the products leaving the surface is not well defined.) It is thought that two factors of major importance are radiation heat feedback from particles burning in the mainstream to the surface and the nature of the flow and turbulence profiles near the surface. The apparatus sketched at the bottom of Page 2 will be used to study these effects and define at least qualitatively the important processes. Diagnostics will include high-speed photography, laser schlieren, LDV and laser raman spectroscopy for definition of the nature of products leaving the surface and processes occurring in the gas phase, while imbedded thermocouples and heat flux gages will be used to determine subsurface temperature profiles and heat feedback fluxes (radiative and non-radiative). Sampling probes may also be employed for definition of ablation products. Construction of this facility is currently under way.



SINGLE PARTICLE BORON IGNITION/COMBUSTION EXPERIMENT
(INCLUDES STUDY OF $H_2O(g)$ + $B_2O_3(l)$ KINETICS)



CONSOLIDATED GRAIN COMBUSTION MECHANISM EXPERIMENT

- **MAJOR TASKS PLANNED**

(1) Conduct exhaustive critical review of domestic and foreign work on boron ignition/combustion phenomena.

(2) Extensively modify existing single particle boron ignition model, extending it to properly treat the effects of H_2O on particle ignition.

(3) Develop a mechanistically accurate model for boron particle combustion in the kinetics-controlled regime.

(4) Develop a boron cloud ignition model.

(5) Develop stirred reactor and directed-flow models of boron cloud combustion using unit models developed in above tasks.

(6) Evaluate feasibility of various approaches to measuring kinetics of $B(s) + O_2$, $B(s) + H_2O$, $B(s) + CO_2$.

(7) Define experiments to quantify problem of conversion of $HBO_2(g)$ to $B_2O_3(l)$.

(8) Experimentally study kinetics of $B_2O_3(l) + H_2O$, using flat-flame burner.

(9) Experimentally identify intermediates appearing in boron combustion.

(10) Use flat-flame burner techniques to obtain ignition and burn-time data for single boron particles in the 5 to 25 micron size range.

(11) Study conversion of boron in a CTRZ reactor.

(12) Investigate the flame structure associated with burning of a consolidated boron grain in an air crossflow.

(13) Experimentally evaluate the effects of boron ignition promoters.

(14) Experimentally study ignition delay times for boron dust clouds.

(15) Measure boron dust cloud flame speeds as functions of various parameters.

- **ACCOMPLISHMENTS TO DATE**

(1) Literature review completed and presented as a paper at the 18th JANNAF Combustion meeting.

(2) Single particle ignition modeling nearly complete.

(3) Flat-flame burner facility completed and single particle ignition/combustion testing initiated.

(4) Consolidated grain combustion mechanism test apparatus designed and under construction.

ABSTRACT: AFOSR CONTRACTORS MEETING (FALL, 1981) CHARLES L. PROCTOR

"FLAME EFFICIENCY, STABILIZATION AND PERFORMANCE IN PREVAPORIZING/ PREMIXING COMBUSTORS"

The prevaporizing/premixing combustor configuration examined in this investigation models the fundamental processes present in ramjets, afterburners, and advanced designs of turbojets. Flame stabilization is accomplished by heat and mass transfer from a recirculation zone to the adjacent shear layer, where fresh fuel/air mixture is ignited. In this investigation a sudden area expansion generates a recirculation zone essentially identical to the bluff-body flame stabilization found in ramjets, afterburners, and turbojets. To simulate prevaporized/premixed combustor inlet conditions, fuel is introduced upstream of the flame zone into preheated air and allowed to vaporize and mix with the air in a fuel preparation tube (Fig. 1a). Operating conditions of the combustor are varied to produce air and fuel rates, pressures and inlet air temperatures comparable to typical gas turbine combustors, i.e., air mass flow rates $\sim$ 1 kg/s, combustor pressure $\sim$ 3 to 8 atm, inlet air temperature $\sim$ 800 K.

Past research on this configuration includes collection and correlation of blowoff data, and collection of efficiency data. The continued research reported here examines the structure of two flames: propane and jet-A, from data obtained by discrete probing using a single geometry, numerical modeling of non-reacting flow fields for a variety of combustor dimensions, and experimental examination of flashback for a propane flame using five geometry variations of the flameholder and the flameholder used in discrete probing.

The tube and disc configuration of figure 1a is the baseline geometry used in this research. Variations to these dimensions are presented in table 1. In ideal circumstances the mass flow split of air between the tube and annulus is equal to the ratio of those two areas and there exists a uniform inlet velocity profile, i.e., annular and tube velocities of equal magnitude. Unfortunately, this ideal condition is difficult to produce due to non-uniformities in the upstream flow, and hardware - such as the fuel injection nozzle. In an attempt to best provide a uniform velocity profile to the combustion zone, a shrouded tube and disc configuration was used for discrete probing and preliminary flashback work. The shrouded tube and disc has nearly a flat velocity profile in the annular region at the plane of the disc and a uniform velocity profile at the tube mouth. Due to the non-idealities stated above, the mass flow split is not exactly equal to the ratio of the annular and tube areas. Thus, a relatively clean inlet velocity profile is produced; however, the inlet velocities at the tube and annulus are not equal. In the case of the simple tube and disc (the flameholder type used for geometry variation), no effort is taken to assist the flow around the disc. The vena contracta produced near the plane of the disc results in significantly increased annular velocities at the plane of the disc.

Table 1. AFOSR Burner Geometries

	D(cm)	d(cm)	L(cm)	D-d(cm)
A	12.7	4.5	14.5	8.2
B	10.8	4.5	14.5	6.3
C	12.7	4.5	8.1	8.2
D	11.7	3.5	14.5	8.2
E	12.7	3.5	14.5	9.2

The experimental data used in characterizing the structure of the propane and jet-A flames were obtained by internal probing of the combustor using a water cooled probe. Gas samples were extracted and analyzed for unburned hydrocarbons (UHC), CO, CO_2, O_2, NO, and NO_x. Temperature and combustion efficiency were estimated using gas analysis results. Presentation of the discrete probing data are in the form of contour plots scaled to the combustor (Fig. 1b). For both flames the inlet air mass flow rate and temperature was 1 kg/s and 800 K, respectively. Propane represented an efficient homogeneous flame at a combustor pressure of 8 atm running at an equivalence ratio of .23. Jet-A, a typical aviation fuel, did not completely vaporize in the fuel preparation tube and consequently produced a hetergeneous flame at the experimental condition 4 atm and equivalence ratio 0.30.

Numerical calculations were made for the non-reacting flow field of the tube and disc configuration using the finite-difference elliptic computer code "CORA2" by D. B. Spalding as adapted for this configuration by the investigators. A variety of inlet conditions and tube and disc dimensions were examined. As a basis for comparison with calculations including non-ideal inlet conditions, initial computations were performed with uniform inlet velocity profiles representing ideal bluff-body obstructions. The shrouded tube and disc computed flow field was examined and compared to experimental data (Fig. 1c). The simple tube and disc geometries were modeled by specifying the mass flow split between the tube and annular regions as indicated by pitot probe results and adjusting the disc dimensions to match the inlet velocity profile. Inlet turbulence kinetic energy was also varied while maintaining a given set of dimensions and flow conditions. These results are presented in the form of contour plots of stream lines and are also scaled to the combustor.

Flashback was studied on five geometries and repeated for geometry A using the shrouded tube and disc. Inlet temperatures between 600 and 800 K were used and combustor pressures ranged between 1 and 8 atm. The fuel propane was used to eliminate hetergeneous effects. A significant number of data were taken to facilitate analysis. In addition, high speed films of the flashback process were made so that the fundamental mechanics could

be studied in detail. Initial analysis on a plot of equivalence ratio vs combustor loading (Fig. 2) indicate that the anticipated trends are evident. Nevertheless, variation in the flameholder geometry, inlet temperature, and mass flow rate are shown to shift the flashback limit. Discussion of various aspects of flashback correlation using the characteristic time technique is offered after presentation of a high speed film of the flashback process.

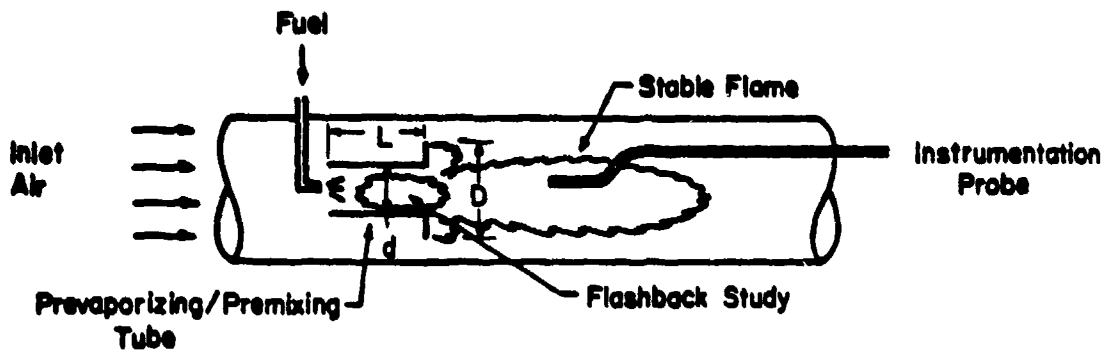


Figure 1a. Schematic of combustor

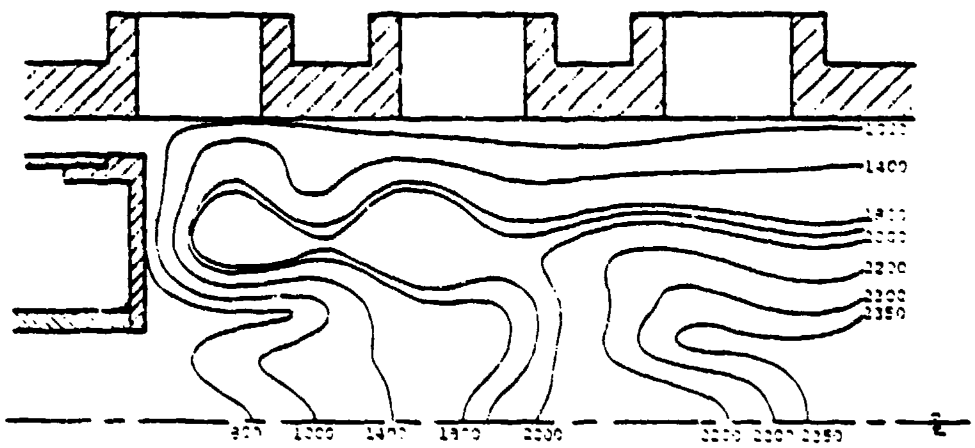


Figure 1b. Temperature contours (K) of propane flame.

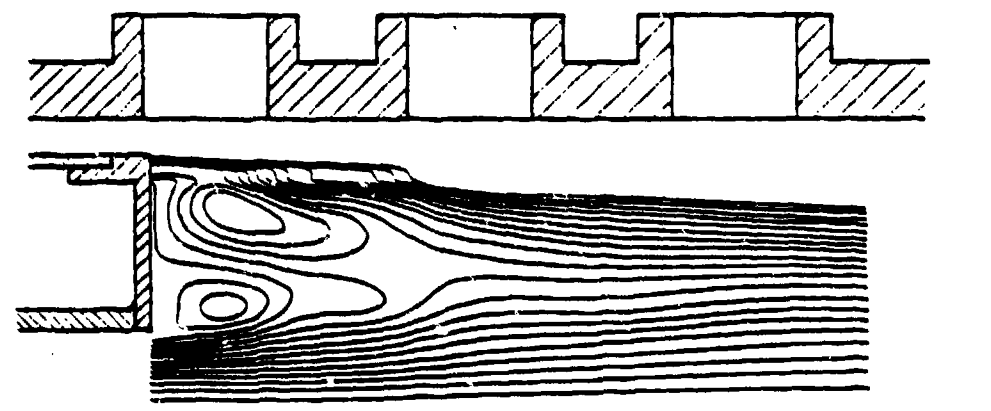
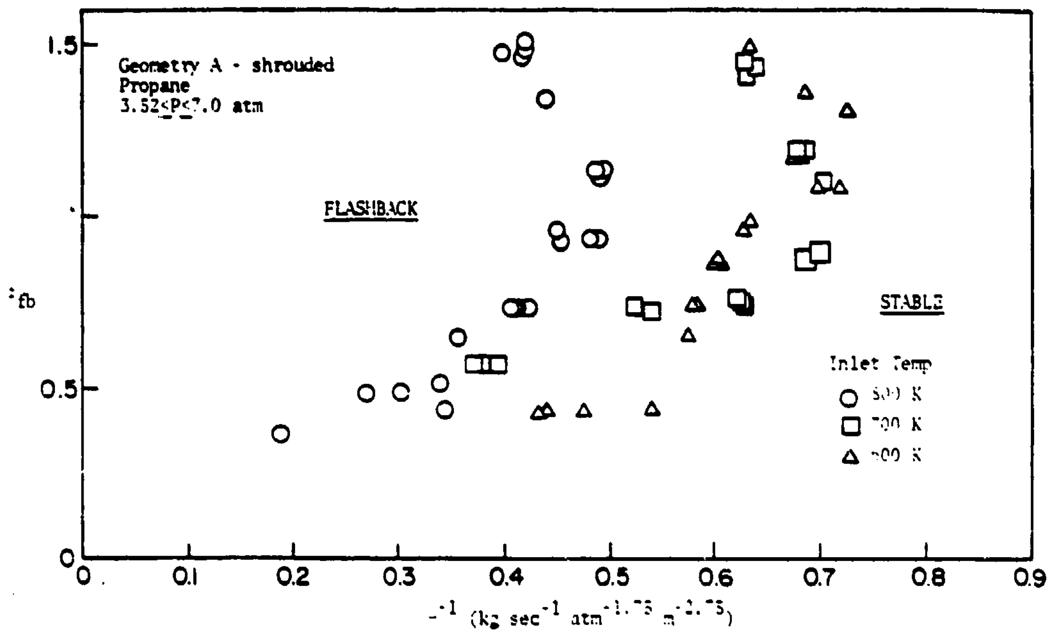


Figure 1c. Streamline contours



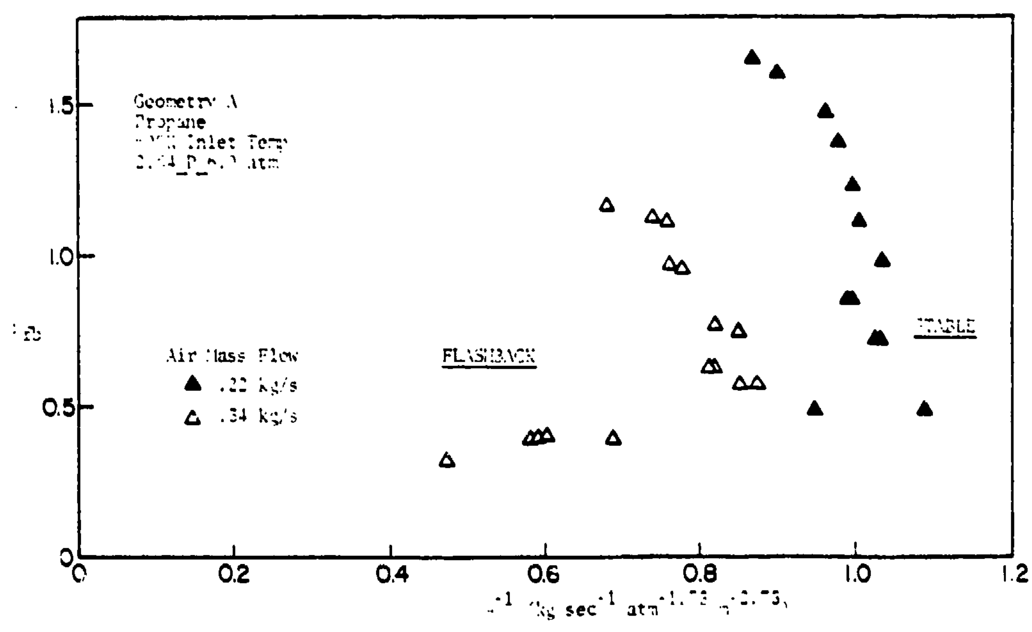


Figure 2. Flashback data

Tuesday PM Session

1:30 Afternoon Chairman

D.F. Stull
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

1:35 Research on Supersonic and Dual Mode Combustion at NASA-Langley Research Center

G.B. Northam
NASA-Langley Research Center

2:00 Combustor Inlet Interactions and Modeling of Dual - Combustion Hypersonic Ramjet Engine

P. Walthrup
Applied Physics Lab/Johns Hopkins University

2:25 Flame Efficiency, Stabilization and Performance in Airbreathing Combustors

A.M. Mellor
Purdue University/KVB-Research Cottrell

2:50 Fundamental Studies of Flame Holding Phenomena on High Speed Reacting Flow Systems

W. Strahle
Georgia Institute of Technology

3:15 BREAK

3:30 Mechanisms of Exciting Pressure Oscillations in Ramjet Engine Environments

F. Culick
California Institute of Technology

3:55 Basic Instability Mechanisms in Chemically Reacting Turbulent Flows

T.Y. Toong
Massachusetts Institute of Technology

4:20 Critical Evaluation of High Temperature Kinetic Data for Combustion and Exhaust Reactions

L.H. Gevantman
National Bureau of Standards, Gaithersburg, MD

4:45 Electrostatic Atomization of Hydrocarbons Spray Patternation Studies

Arnold J. Kelly
Exxon Research & Engineering, Linden, N.J.

5:10 ADJOURN

HIGH-SPEED PROPULSION RESEARCH AT
NASA LANGLEY RESEARCH CENTER

by

G. Burton Northam*

Proposed Abstract for
AFOSR Contractors Meeting on Airbreathing Combustion Research
Clearwater, Florida
November 16-20, 1981

The objective of the NASA-Langley high-speed aircraft program is to develop the technology base necessary for operation of airplane or missile systems in the Mach 3 to 10 flight regime. The overall program covers the basic research areas of propulsion, aerodynamics, and structures, and a large data base has been developed in each discipline. The major effort in the aerodynamics activity has been in defining vehicle configurations and nozzle characteristics when the propulsion system is integrated with the vehicle. The structures activity has been concerned with the design of a regeneratively cooled (H_2) long thermal-cycle-life engine structure; it is currently focused on the design, construction, and test of a hydrogen-cooled engine strut that would demonstrate the needed fabrication techniques and cooling concepts.

The propulsion portion of the Langley program will be highlighted in the presentation. Supersonic combustion ramjet research has been underway at LaRC since 1964 with an emphasis on airframe-integrated scramjets since 1968. The present Langley scramjet concept employs a number of engine modules mounted on the underside of the aircraft. This allows the engine to take advantage of

*Aerospace Engineer, Hypersonic Propulsion Branch, High-Speed Aerodynamics Division, NASA Langley Research Center, Hampton, VA

the vehicle bow shock for inlet precompression and uses the aft body of the vehicle for the nozzle expansion. Proper attention to propulsion system/vehicle integration also produces lower external drag. The engine modules each have fixed-geometry inlets with instream struts to complete the compression process. These struts provide a location for instream fuel injection which improves fuel mixing and minimizes combustor length. Cold flow wind tunnel tests and simulated flight tests with hot flows, both Mach 4 and Mach 7, have demonstrated the fixed-geometry airframe-integrated inlet performance. The concept is self-starting and has high pressure recovery and good capture characteristics over this flight Mach number range.

Two research scale engine modules 8 inches high by 6.4 inches wide using this inlet configuration have been constructed and tested at Mach 4 and Mach 7. Test results indicate good performance at Mach 7 simulated flight conditions when Silane SiH_4 (pyrophoric) is used to aid flameholding. At Mach 4 test conditions, the engine experienced a combustor-inlet interaction when the equivalence ratio was increased beyond the valve for which thermal choking was predicted. The tests therefore quantified the supersonic combustion limits and established the requirements for dual-mode combustor operation.

Experiments using direct-connect test techniques with single strut hardware simulating the flow about the center strut in the fixed-geometry inlet have recently been completed. The results indicate that with some slight modifications, the fixed-geometry scramjet concept should be able to operate with dual-mode combustion. Depending somewhat on the flight Mach number simulated by the test stream (i.e., total temperature), the combustion mode can be shifted from subsonic to supersonic by simultaneously shifting the fuel injection from mostly parallel to mostly perpendicular to the local stream.

The experimental component and engine research described above is conducted in five primary facilities of the type and characteristics listed below:

Facility	Type	Maximum Range	Size
Ceramic Heated Combustion	Pebble bed heater	4000°R 800 psi	5 #/sec
Supersonic Combustor Test Stand (TC #2)	H_2 fueled heater	4500°R 450 psi	100 #/sec
M = 4 Test Facility (TC #1)	H_2 fueled heater	2200°R 175 psi	13" x 13" 80 #/sec
M = 7 Scramjet Test Facility	Arc heater	4000°R 600 psi	13" x 13" 5 #/sec
8' HTST planned O_2 replenishment	CH_4 fueled combustion	4000°R 1200 psi	8' dia. 1000 #/sec
M = 4 & 7 Test Facility, General Applied Science Labs. (GASL)	H_2 fueled heater (partially NASA owned facility)	4000°R 1500 psi	13" x 13" 35 #/sec

Related to more fundamental research activities, two- and three-dimensional computational fluid dynamic (CFD) codes are being developed to analyze and model inlet and combustor performance. This activity is augmented with numerous contracted programs to develop and evaluate turbulence models, improve 3-D techniques, study the influence of temperature fluctuations on combustion and develop global combustion models that can be used to reduce computational time. In addition, a combustion diagnostics activity has been recently initiated to develop nonintrusive measurement techniques for application in the test facilities mentioned. Coherent Anti-Stokes Raman Spectroscopy (CARS) system is being developed for measurements in supersonic flames. The results will be used to verify CFD codes that are/have been developed and to assess the limits of validity of the turbulence models in supersonic reacting diffusion-limited flows.

Finally, Langley also has a program objective to identify critical technology areas that are necessary to apply the integrated ramjet/scramjet technology to the Navy's Wide Area Fleet Defense mission using restraints imposed by box launchers currently used in the fleet. A cooperative APL-JHU/NASA research program is currently being formulated to explore inlet design issues for this mission.

Salient results from the various experimental and analytical research programs will be presented, and implications for future research and possible applications will be discussed.

COMBUSTOR/INLET INTERACTIONS AND MODELING OF DUAL-COMBUSTION RAMJET ENGINES

Paul J. Waltrup, Frederick S. Billig and Joseph A. Schetz (Consultant)

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Laurel, Maryland 20707

Technical Objective: To develop a basic knowledge and understanding of the overall engine cycle, individual component flowfields and engine thermochemistry in hypersonic dual-combustion ramjet engines (Fig. 1). This basic understanding comes from accurate analytical models of the engine and its components plus concomitant experiments.

Approach: The approach taken here is twofold. The first is experimental and limited to the combustion induced, shock-separated region between the air inlet and the entrance of the supersonic combustor (Fig. 2). Initially, this effort will experimentally characterize the flowfield in this region over a wide range of test conditions and provide the details needed to better understand the complex shock/boundary layer interactions which occur. These data will then be used to develop a semi-emphferical model for predicting the length of air duct needed between the inlet and supersonic combustor to prevent these combustion induced disturbances from degrading the inlet's and, therefore, overall engine's performance. The second approach is an analytical effort in which multiple models of the dual-combustion process as well as an overall engine cycle model are being developed and compared with the limited available experimental data. The former will enhance the understanding of the details of the combustion process, such as flow profiles, wall skin friction, wall heat transfer and chemical kenetics, while the latter will provide fundamental global predictive techniques for the overall engine and parametric variations thereof.

Progress: Since the inception of this program in August of 1980, the following progress has been made:

Design and fabrication of the experimental hardware needed for the combustor/inlet interaction experiments is complete. Installation and instrumentation of the hardware is ~90% complete. Initial testing at $M_{ci} = 2.5$ is expected to begin this fall. Additional test with $M_{ci} = 2$ and 3 are also planned.

An initial model simulating the coaxial mixing and combustion process in the supersonic combustor of a dual-combustion ramjet engine has been developed along with a preliminary analysis for predicting the skin friction and heat transfer losses along the combustor walls (Fig. 3). The effects of changing thermochemistry are included in both. The results to date are encouraging in that they are able to predict the length of the combustion flame zone and provide radial and axial flow profiles within the combustor (Fig. 4). In addition, predicted values of wall skin friction and heat transfer show that both increase with increasing combustor heat release (Fig. 5), something heretofor not predicted but observed in past experiments on supersonic combustion ramjet engine combustors. Additional refinements to these analyses, including improved thermochemistry and transport properties, are currently being investigated.

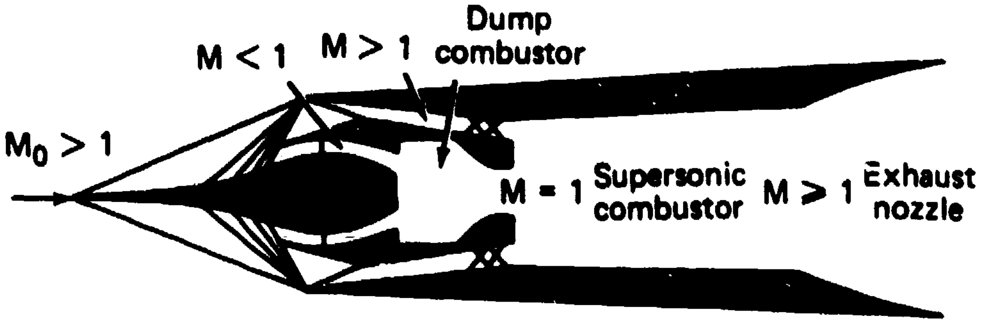

Fig. 1 Schematic of dual combustion ramjet engine.

Dimensions are in inches.

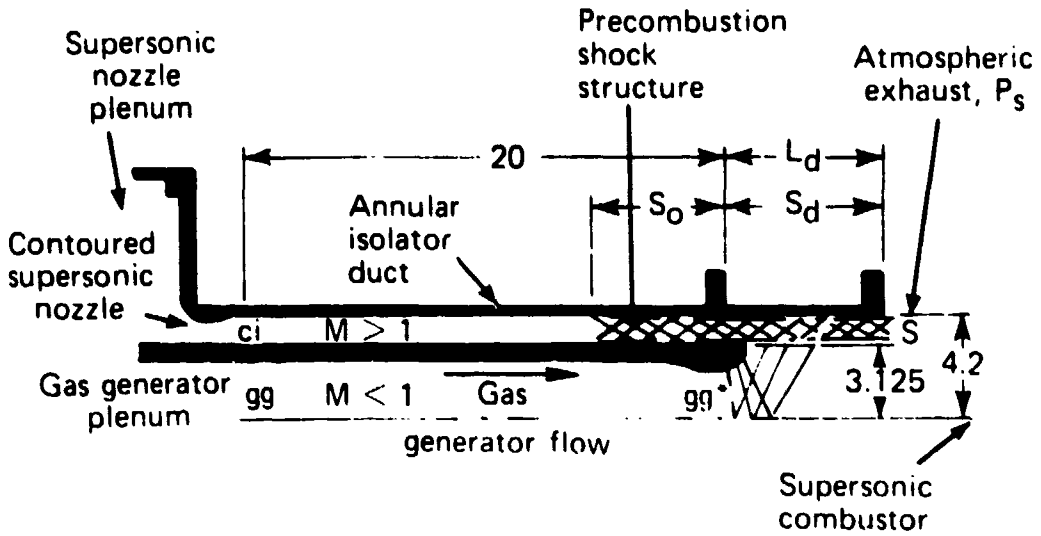

Fig. 2 Schematic of combustor/inlet interaction hardware for DCR engine.

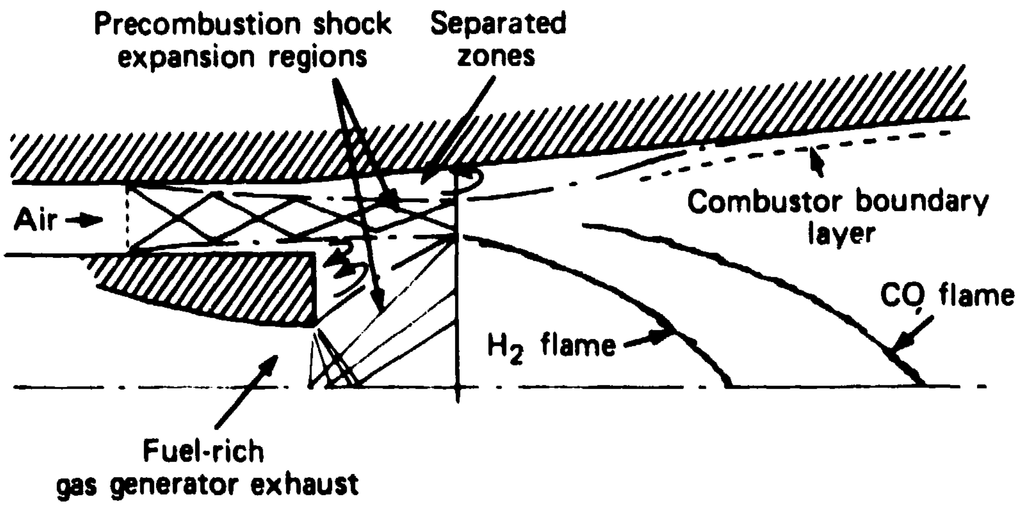

Fig. 3 Model of supersonic combustor.

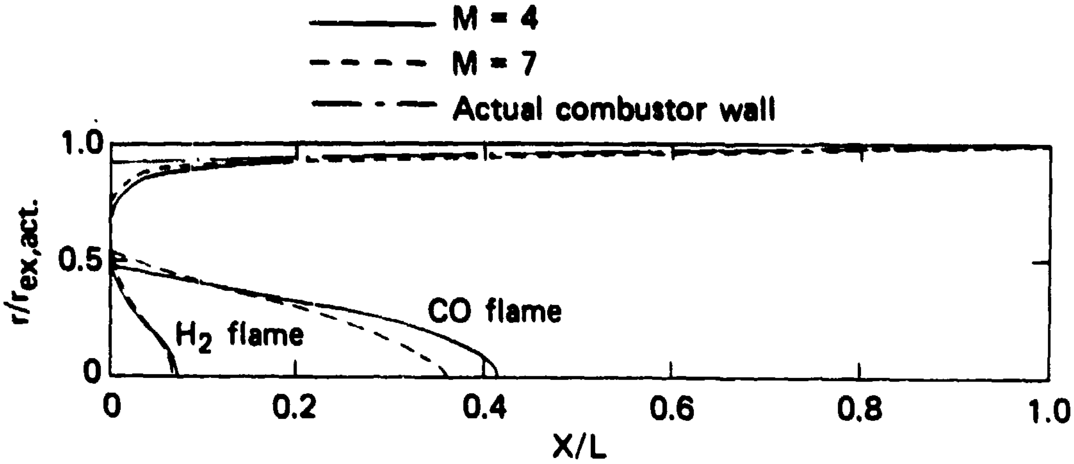

Fig. 4 Predicted combustor and flame sheet contours for $M_0 = 4$ and 7 flight with ER = 0.5.

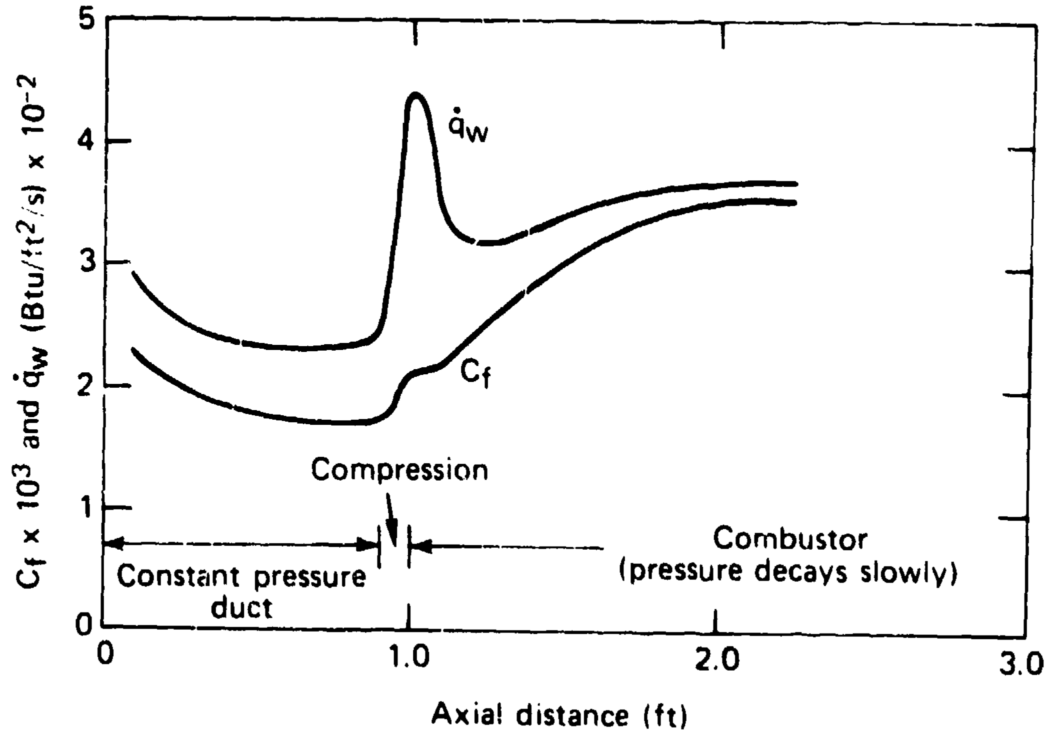

Fig. 5 Combustor wall skin friction coefficient and heat flux distributions for $M_0 = 7$ flight for ER = 0.5.

FLAME EFFICIENCY STABILIZATION AND PERFORMANCE IN AIRBREATHING COMBUSTORS

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KVB-Research Cottrell
Santa Ana, Ca
(AFOSR-77-3446)

ABSTRACT NOT AVAILABLE

FUNDAMENTAL STUDIES OF FLAME HOLDING PHENOMENA ON HIGH SPEED REACTING FLOW SYSTEMS

W. Strahle
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(F49620-78-C-0003)

<u>ABSTRACT NOT AVAILABLE</u>

PRESSURE OSCILLATIONS IN RAMJET ENGINES

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California Institute of Technology
Pasadena, CA 91125

This program broadly comprises three parts, devoted to experiments in a laboratory dump combustor; analysis of combustion processes enhanced by vortex shedding as a fundamental mechanism for causing pressure oscillation; and acoustics analyses as a framework for treating the general problem of pressure oscillations. These subjects will be described in inverse order. The report covers the first year of a new program.

1. Analysis of Acoustics

Much of this work consists initially in extension of previous investigations of pressure oscillations in rocket combustors and afterburners. The general problem is one of self-excited oscillations ultimately caused by the energy released in combustion processes. Analysis of linear behavior therefore provides conditions of stability and relations among the various processes for gain and loss of energy. Nonlinear behavior is required if an unstable motion is to reach a limiting amplitude, that is, the system will execute a limit cycle. Work is in progress covering both linear and nonlinear problems.

The main features of a ramjet engine which distinguish it from other combustion systems are the supersonic inlet/diffuser and the configuration of the combustion chamber. So far as pressure oscillations are concerned, the diffuser presents a boundary condition which may in first approximation be represented by a single normal shock wave. One problem then is to determine the response of the shock to pressure fluctuations. The linear problem, which amounts to finding the admittance or impedance function, has been treated elsewhere. In this program, work has been started to investigate nonlinear behavior, especially for comparison with shock displacements being measured

by other organizations.

A major consequence of the geometry, which is designed to stabilize the combustion field in flow with an abrupt change of area, is that the average flow field is very different from those in other systems. Because analysis of the acoustics requires knowledge of the average flow field, a large part of the effort to date has been devoted to finding a suitable simple and realistic representation. It need not be as elaborate as necessary for precise calculations of, say, temperature profiles and combustion efficiency, simplicity is desirable to ease the acoustics analysis. We have achieved only modest success at this time. Work has also begun to work out the proper means of accounting, in the acoustics analysis, for the peculiar form of the mean flow field, with emphasis particularly on zones of separation and recirculation.

Ultimately, the influences of the Mach number of the average flow and the amplitude of oscillation are important items for practical considerations. An idealized analysis, for longitudinal waves in a uniform duct, is being completed, preparatory to more realistic treatments later in this program.

It is our intent that the analysis of the acoustics should be so constructed as to accommodate both the analysis of a fundamental mechanism, involving vortex shedding and the experimental work being pursued in the other parts of this program.

2. Analysis of Unsteady Combustion and Vortex Shedding

High frequency instability in combustors is often excited by a vortex shedding phenomenon, the frequency and amplitude of which are determined by the acoustic oscillation itself. An essential ingredient of this mechanism is the entrainment of combustible mixture into a vortex structure and the creation of a pressure pulse, some time subsequent to the entrainment.

In a ramjet engine, the vortex shedding occurs at a bluff body flame-holder, or in the shear layer formed by flow past a dump. The actual geometry is easily idealized for purposes of analysis. Calculations of this phenomenon have been made based upon a model in which a pre-mixed flame, initially coincident with the horizontal axis, is distorted by a vortex located at the origin. The flame is "wound" about the origin into a laminated structure of combustible mixture and combustion products, separated by the flame front. During this process, the flame is strained severely along its length, initially at such high rates that the flame is extinguished. At larger radii, where the strain rate is lower, the burning continues, eventually propagating into the core when a considerable amount of combustible gas remains. Some results of such a calculation are shown (figure 1) in which the fuel consumption augmentation by the vortex, made dimensionless by the circulation Γ and the thermal diffusivity $\sigma \equiv k/C_p\rho$, is given in terms of the dimensionless time. Here τ_c is the effective time constant of the chemical reaction involved in the combustion process. In summary, the combustion pulse occurs about one chemical time after the initiation of the vortex; the amplitude of the pulse varies as $\Gamma^{2/3}$ and hence increases as the gas velocity in the burner, and hence the strength of the vortex, increases.

The result suggests that a mode of certain frequency will be excited where the chemical time τ_c is about equal to the period of the oscillation. Data of C. L. R. Barker, taken several years ago, are shown in figure 2 where the lean limit of high frequency instability was measured for a wide variety of gaseous fuels having different chemical time values at the stoichiometric mixture. If the mechanism described above were accurate, the onset of instability would occur at an equivalent ratio giving a fixed time delay, a chemical time. The data show the rather striking accuracy of this concept.

3. Experiments in a Laboratory Dump Burner

An experimental apparatus has been modified to allow its use for the study of combustion instabilities in a dump burner configuration or in an afterburner configuration (with a bluff body flame holder). A premixed stream of fuel and air is supplied to the burner from a blow down air supply. The burner inlet duct is 2.6 cm by 7.6 cm and the cross-section downstream of the dump region can be expanded to a 5.2 by 7.6 cm duct. The burner, downstream of the dump station is 50 cm long and a nozzle closure can be used at the exit of the duct. The system is two-dimensional and can be Vycore side walls (the 2.6 to 5.2 cm dimension) used to allow visual spectrographic and schlieren observations of the flow field.

The apparatus has been operated with methane and hydrogen fuel in the afterburner configuration and we are presently beginning operation with the dump burner. Problems with the short operating period of the system (20-60 sec) and ignition systems have been slowing our development of the apparatus, and keep the cold air speed upstream of the dump or flameholder station below 36 m/s.

FIGURE 1

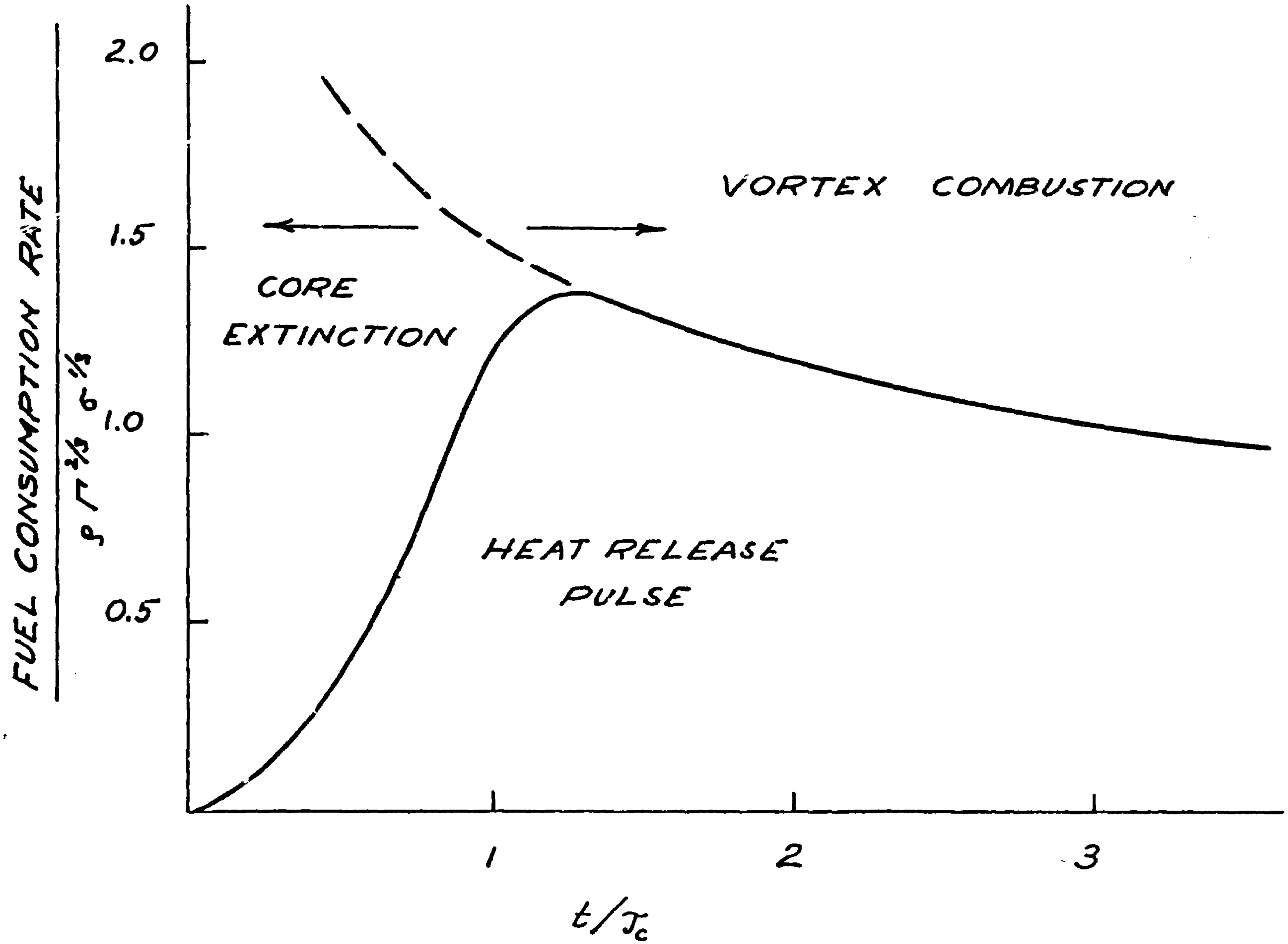
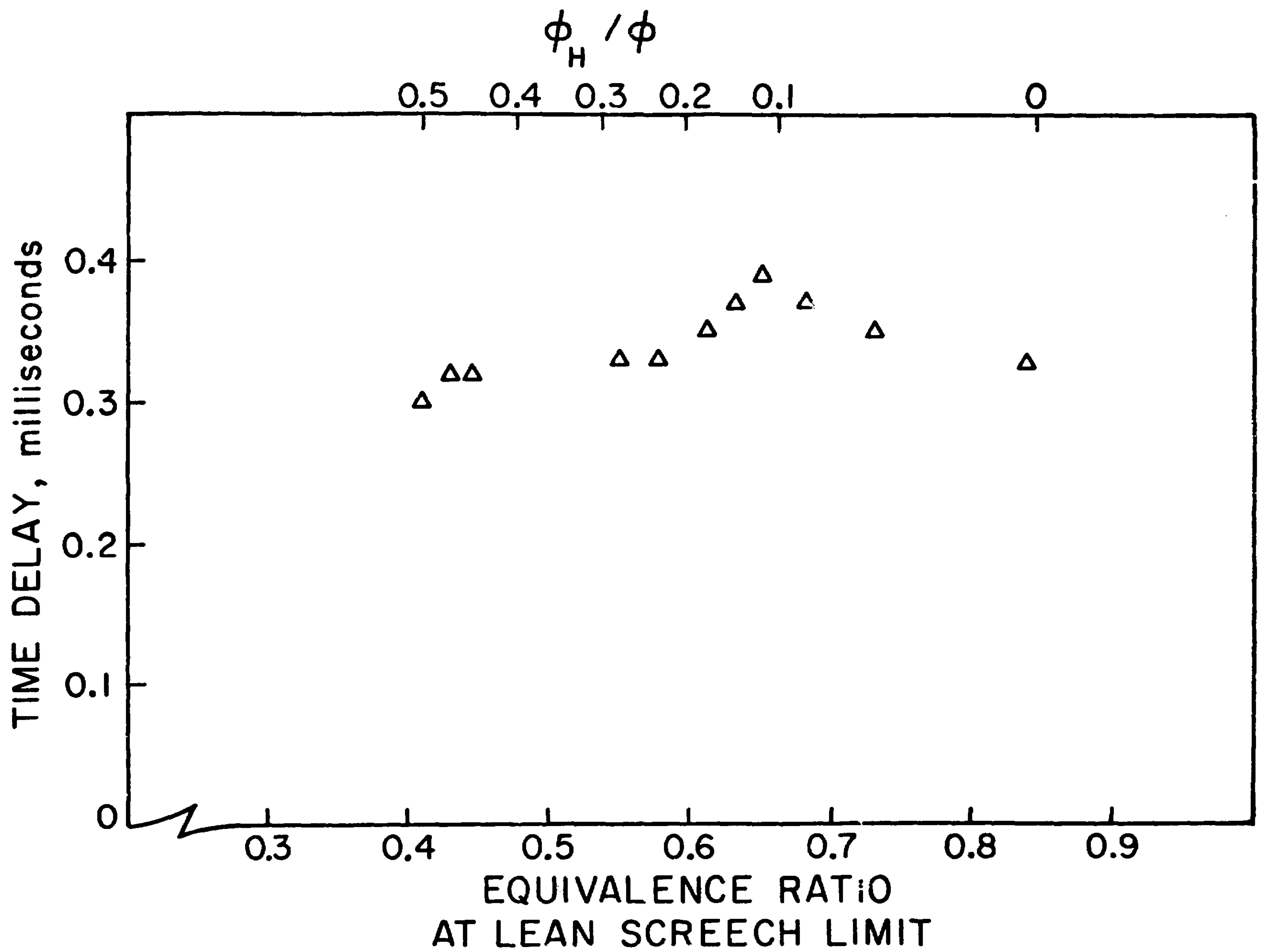

FUEL CONSUMPTION RATE
ρ Γ 2/3 σ 1/3
2.0
1.5
1.0
0.5
CORE
EXTINCTION
VORTEX COMBUSTION
HEAT RELEASE
PULSE
1
2
3
t/τc

FIGURE 2



ϕ_H / ϕ
0.5
0.4
0.3
0.2
0.1
0
TIME DELAY, milliseconds
0.4
0.3
0.2
0.1
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
EQUIVALENCE RATIO
AT LEAN SCREECH LIMIT

BASIC INSTABILITY MECHANISMS IN CHEMICALLY REACTING SUBSONIC AND SUPERSONIC FLOWS

Tau-Yi Toong

Massachusetts Institute of Technology   Cambridge, Massachusetts 02139

The main objective of this research is to determine the major mechanisms governing the efficiency, power output and pollutant emission of propulsion devices as well as safety against explosions. Three problems are being studied: one is related to the initiation and the sustenance of gaseous detonations; the second, the triggering and the sustenance of low-frequency instability in dump combustors; and the third, the temporal development of turbulent combustion.

The structure, sustenance and stability of detonations are believed to be the result of complex interactions between chemical kinetics and gas dynamics. These interactions also govern the requirements for their initiation, in terms of the power density, energy density and energy-deposition duration or volume. Figure 1A shows the temporal development of shock pressure after a piston is set in motion in a detonable mixture. Theory shows that for direct initiation, the piston should remain in motion for a time interval, at least, equal to the induction time. In the case of Fig. 1A, this critical time $\hat{t}_p$ is between 1.3 and 1.5. Figure 2A shows that the predicted energy and power requirements agree quite well with the experimental findings.

Figure 1B illustrates the mechanism which sustains the longitudinal instability of a shock-reaction zone complex. Analysis shows that the interaction between irreversible temperature fluctuations and finite reaction zone induces an oscillatory energy-source field, which then leads to shock perturbations and thereby the temperature fluctuations. Predicted periods of low- and high-frequency modes are found to agree well with those observed in hypersonic blunt-body flow experiments (cf. Fig. 2B).

One major problem related to the use of dump combustors in propulsion devices is to eliminate the low-frequency oscillations. Figure 1C shows typical low- and high-frequency pressure oscillations observed in a combustor, in which the flame is stabilized by the use of a flame holder or simply a recirculation zone. The low-frequency mode is believed to be triggered and sustained by the interactions between non-uniform entropy zones and pressure waves. Figure 2C illustrates the mechanism. Rarefaction waves incident on the flame zone (a) cause the flame to stretch (b) and to separate (c), forming a region of low entropy. The non-uniform entropy zones then generate compression (d) and rarefaction waves (e), as they are convected through the choked nozzle. Thus, the cycle repeats itself. Predicted frequencies are found to agree reasonably well with the observed values (cf. Fig. 2C-f).

One promising way to achieve in-depth physical understanding of turbulence-combustion interactions is to study the temporal development of turbulent characteristics from laminar combustion. Figure 1D shows the development of instability in a shear flow, where vortices are formed due to the growth of disturbances. Such growth rates are affected by the presence of chemical reaction, as shown in Fig. 2D.

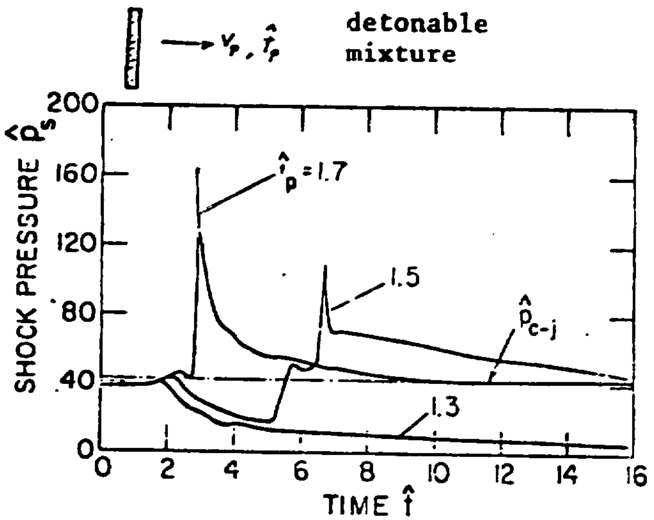


Fig. 1A

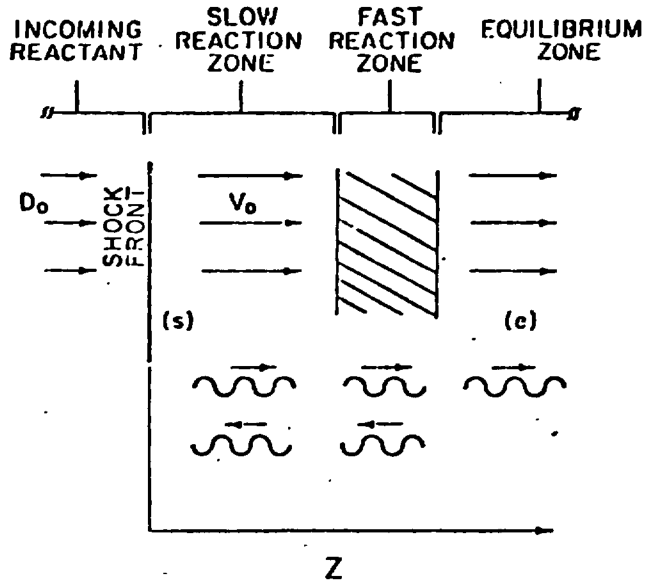


Fig. 1B

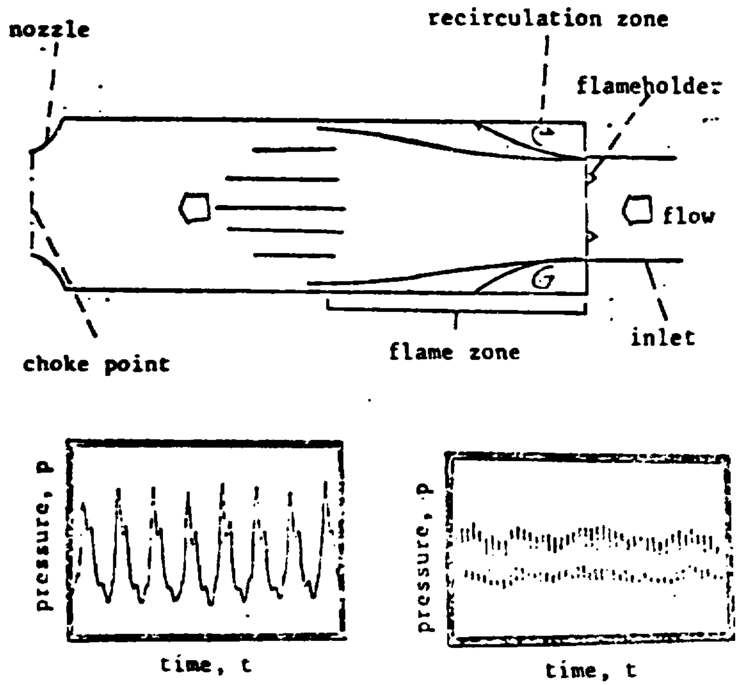


Fig. 1C

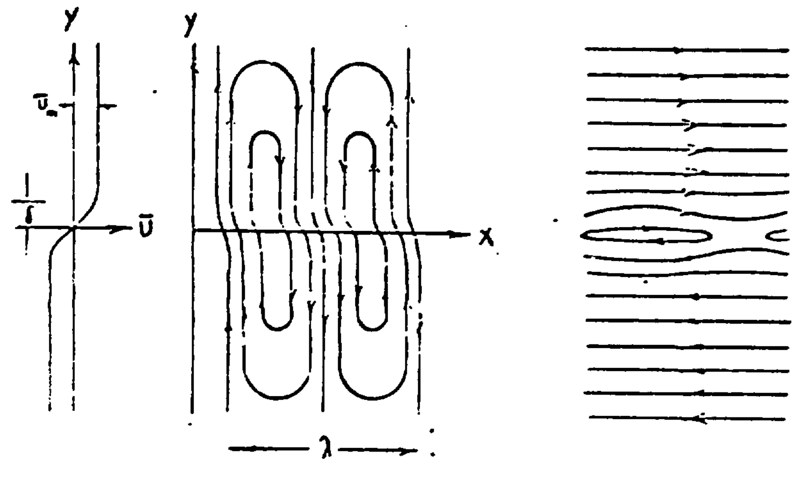


Fig. 1D

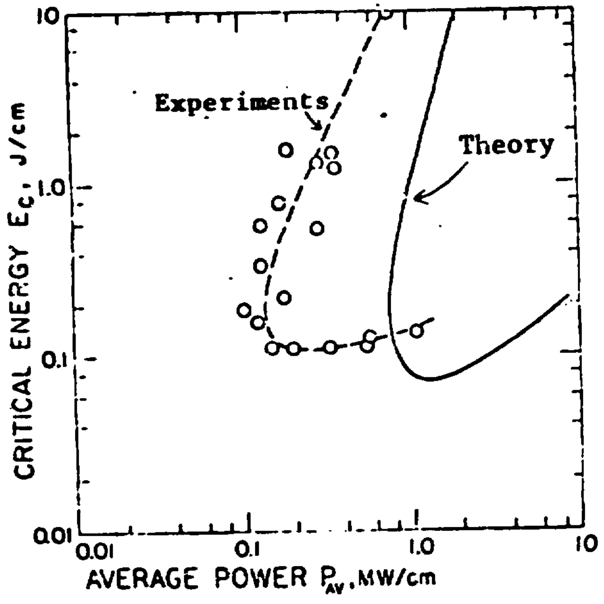


Fig. 2A

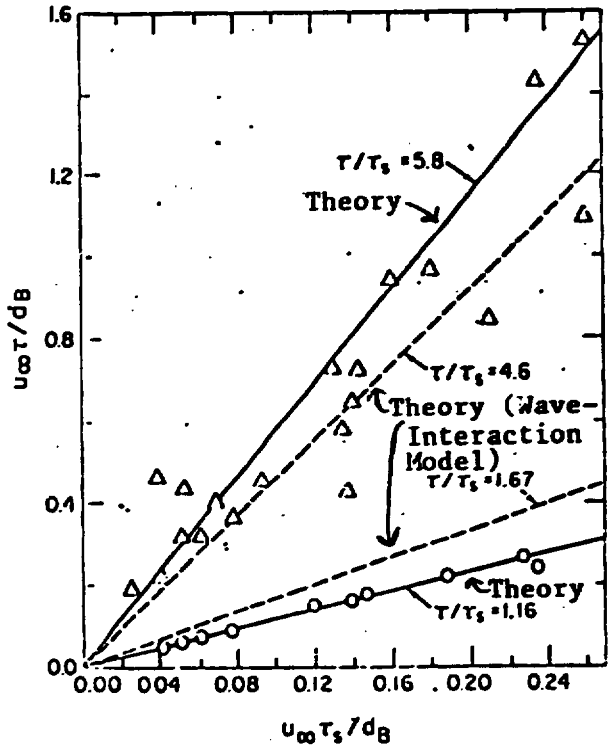


Fig. 2B

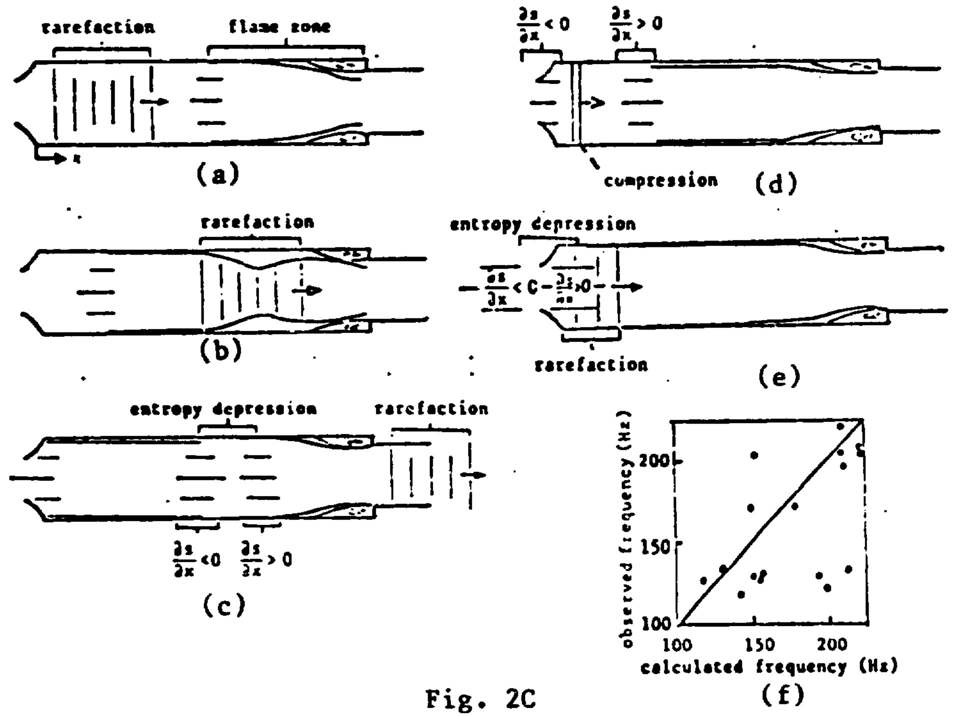


Fig. 2C

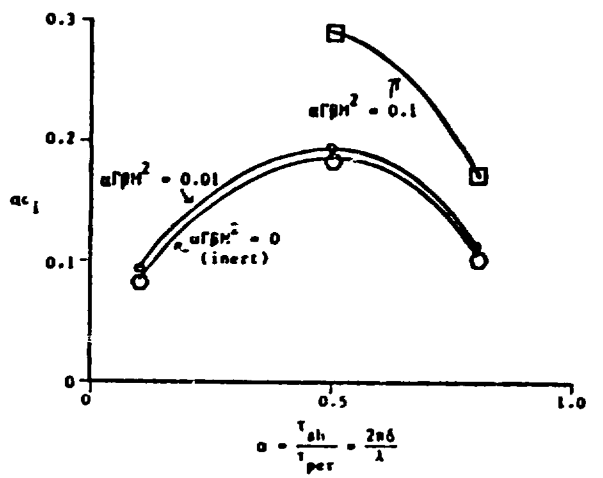


Fig. 2D

EVALUATION OF HIGH TEMPERATURE CHEMICAL KINETIC DATA: ESTABLISHMENT OF A DATA SHEET SERIES

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Post Office Box 92957
Los Angeles, California 90009

Lewis H. Gevantman
Office of Standard Reference Data
National Bureau of Standards
Washington, DC 20234

This project, now entering its fourth year, is dedicated to the issuance of data sheets containing chemical kinetic parameters on high temperature reactions occurring in the plumes of jets and rockets. The data are compiled from all available open literature sources evaluated in light of the best possible information on experimental as well as theoretical approaches. Peripheral information is included when pertinent to the analysis of the rate parameter in question. However, considerable detail must of necessity be omitted because of space restriction, and only key measurements are cited. Figures 1 and 2 show the two sides of a complete data sheet. The data sheets are distributed to approximately 200 practicing kineticists. In carrying out an evaluation of rate parameters on key elementary reactions, considerable weight is given to the assembly of the data and such questions as: Are the data sound? Is there sufficient information for reanalysis? Is the experimental technique reliable? Generally, if six or more measurements agree within 20%, little reanalysis is necessary. Theory (transition state) is applied to assure agreement with experiment and when extrapolating to high or low temperature. However, problems do exist in applying the theory, and where such difficulties exist they appear in the discussion section of the data sheet, Generally, the rate constant values recommended range from 10% to within a factor of 2, although most fall in the smaller error limit.

To date a total of 30 data sheets have been prepared. A paper including the first 20 sheets has been submitted for publication in the Journal of Physical and Chemical Reference Data (JPCRD). Other publications will soon appear on the application of theory to certain types of reactions. Future data sheets will address reactions in advanced propellant systems, e.g., Al/O, B/O, and B/F, and reactions involving OH with alkanes. Some consideration will also be given to hydrazine reactions.

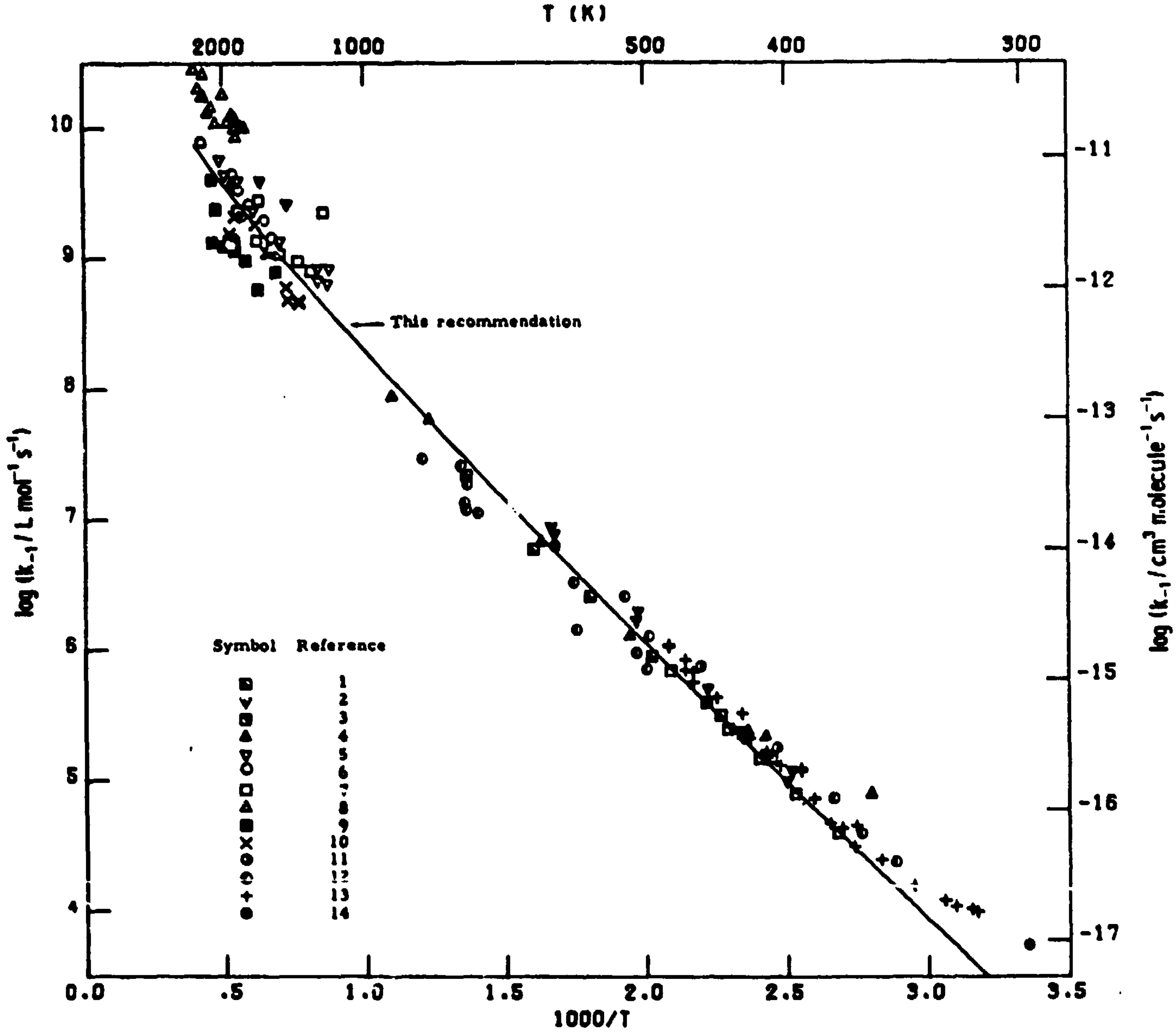
In addition to the work cited above, it is worth noting ongoing related work sponsored by the Department of Energy (DOE) and the National Bureau of Standards (NBS) which is administered by the Office of Standard Reference Data (OSRD). The DOE has sponsored data compilation and evaluation projects concerned with combustion kinetics. Two publications will appear in the NSRDS-NBS series. One lists all of the experimental sulfur reaction rate constants, while the other lists rate constants for reactions of hydrogen, oxygen, nitrogen, sulfur, and hydrocarbons C_1 to C_{10}. Recently another publication on halogen- and cyanide-containing species, by D. L. Baulch and his coworkers, was issued as a supplement to Volume 10 of the JPCRD. New efforts on the kinetics of metastable excited species and on ionic reactions are being pursued. Finally, two CODATA-supported efforts should also be noted. The first involves an update of the data sheets on evaluated rate parameters for reactions in the atmosphere (to be published in the JPCRD), and the second, to be published as a CODATA Bulletin, lists data centers engaged in the evaluation of chemical kinetic parameters.

$$H + OH \underset{-1}{\overset{1}{\rightleftharpoons}} O + H_2$$

ΔH^0_{298} = -8.54 ± 1.3 kJ mol^{-1}(-2.04 kcal mol^{-1}) ΔS^0_{298} = -6.72 ± 0.06 J $mol^{-1}K^{-1}$(-1.61 cal $mol^{-1}K^{-1}$)

K(T) = 0.445 exp(1030/T)

The uncertainty in log K is ±0.2 at 298 K, decreasing to ±0.06 at 1000 K and ±0.02 at 5000 K.



RECOMMENDED RATE COEFFICIENTS

k	k(T)	Range	k(298)	Units
k_1	8 x 10^6 T exp(-3450/T)	298-2500 K	8 x 10^4	L $mol^{-1}s^{-1}$
	1.3 x 10^{-14} T exp(-3450/T)		1.3 x 10^{-16}	cm^3 molecule$^{-1}s^{-1}$
k_{-1}	1.8 x 10^7 T exp(-4480/T)	298-2500 K	5.5 x 10^3	L $mol^{-1}s^{-1}$
	3.0 x 10^{-14} T exp(-4480/T)		9 x 10^{-18}	cm^3 molecule$^{-1}s^{-1}$

Uncertainty in log k_{-1}: ±0.2, 400-1000 K, increasing to ±0.3 at 2500 K and $^{+0.5}_{-0.2}$ at 298 K. Uncertainty in log k: ±0.3 400-2500 K, increasing to $^{+0.7}_{-0.4}$ at 298 K. k_1 is calculated from k_{-1} and K(T); its uncertainty reflects the uncertainties in both of those quantities.

(October 1980)

$H + OH \rightleftharpoons O + H_2$

THERMOCHEMICAL DATA

Thermochemical data for all species are taken from unpublished supplements to the JANAF Thermochemical Tables dated 31 March 1977 and 30 June 1977. The analytic expression chosen for K(T) matches equilibrium constants calculated from these data to within 1% between 250 and 5000 K.

MEASUREMENTS

There have been approximately 30 published studies of k_{-1} over the temperature range 300 - 2500 K, but no direct measurements of k_1. The graph shows the measurements of k_{-1} that appear to be the most accurate.[1-14] Only absolute measurements are plotted, partly for visual clarity, and partly because the rate coefficient of Reaction -1 is at least as well known as the rate coefficients of the various competing reactions. The experimental data have been reviewed by Baulch et al.[15] and Dixon-Lewis and Williams,[16] wherein may be found references to all papers, published through 1974, reporting measurements of k_{-1}. Subsequent to these reviews, five additional studies have appeared.[12-14,17,18]

High-temperature studies in which mixtures of H_2-O_2-Ar were shock heated and the exponential growth of free radicals (H, O or OH) measured have been reanalyzed.[19] Of the 713 such measurements, 327 were found to yield a value for k_{-1} with a precision in log k_{-1} better than ±0.4. A representative sample of these determinations are plotted.[5-10]

CALCULATIONS

Walch et al.[20] performed a transition-state calculation of k_{-1}, the results of which largely agree with experiment.

DISCUSSION

Both Refs. 15 and 16 agree on a value of $k_{-1} = 1.8 \times 10^7\ T \exp(-4480/T)$ over the temperature range of 400 - 2000 K, with an uncertainty of about ±30%. This expression fits most of the data within experimental error, and we see no reason to seek an alternative. There is somewhat more uncertainty in the values of k_{-1} below 400 K; the experimental data suggest that the recommended expression for k_{-1} may predict too high values. At 298 K we recommend the results of Light and Matsumoto,[14] $k_{-1} = 5.5 \times 10^3$, but assign it a large uncertainty, $\Delta \log k_{-1} = {}^{+0.5}_{-0.2}$.

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Figure 2

Electrostatic Atomization of Hydrocarbons
Spray Patternation Studies

Arnold J. Kelly

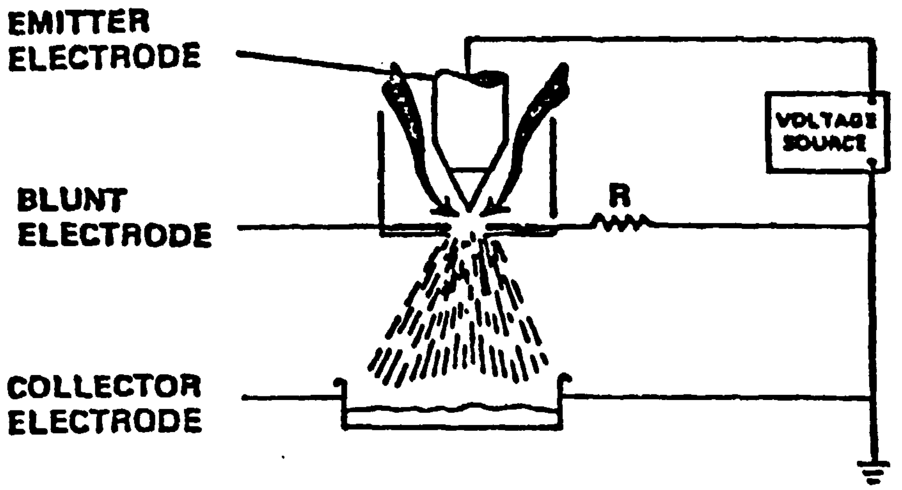
Exxon Research & Engineering Co., Linden, NJ

It has recently been established that all fluids can be electrostatically atomized in a predictable manner which depends upon their charge density level. This fact is embodied in the Spray Triode atomizer which produces high charge density fluids at useful flow rates by direct charge injection. As schematically illustrated in Figure 1 the Spray Triode incorporates two submerged electrodes, a cathode emitter and a blunt anode which together function as an immersed field emitter electron gun. Work that has been conducted since its inception in 1976 has shown that the steady-state operational characteristics of the Spray Triode and the behavior of its plume exhibit an array of characteristics that could be of use in spray combustion applications (cf. Figure 1).

Recent work has been directed toward elucidating the behavior of Spray Triode patternation changes in response to operating conditions. A self-consistent theoretical model that describes the temporal and spatial development of charged droplet plume profiles in response to electrostatic and aerodynamic forces is now available. Figure 2 illustrates the plume profile that is expected to prevail for a 112μm radius orifice Spray Triode (8.8 mil orifice diameter) flowing 0.6 mL/sec of a 845 kg/m^3 dense liquid into quiescent atmospheric air. In this instance operation is at 7700 V and 60μm diameter droplets are formed with charge densities of 1.95 C/m^3. The plume ultimately impinges on a plane that is 20 cm from the spray orifice. The individual tick marks on the profile are 1/2 msec apart. This, and similar calculations for combustion gas conditions, reveals, that electrostatic spray plumes can undergo useful penetration and dispersion on time scales that are appropriate for diesel and fuel injected engine applications.

General agreement exists between the calculated and actual plume profiles. The photographic insert of Figure 2 is of a Spray Triode device that is operating under the conditions noted. The plume is actually quite symmetric but the non-uniform lighting from the right gives the appearance of asymmetric development. For scaling purposes the outside diameter of the Spray Triode used in this test is 9 mm. Beyond this form of comparison no quantitative testing to probe the general validity of the profile model has been undertaken for either steady-state or transient operation. Support for such a study is now being sought. It is the goal of this proposed effort to develop a quantitative predictive model of electrostatic sprays that can be used to portray these plumes in sufficient detail so that they can be used as the basis for electrostatic spray droplet combustion analysis work.

SPRAY TRIODE

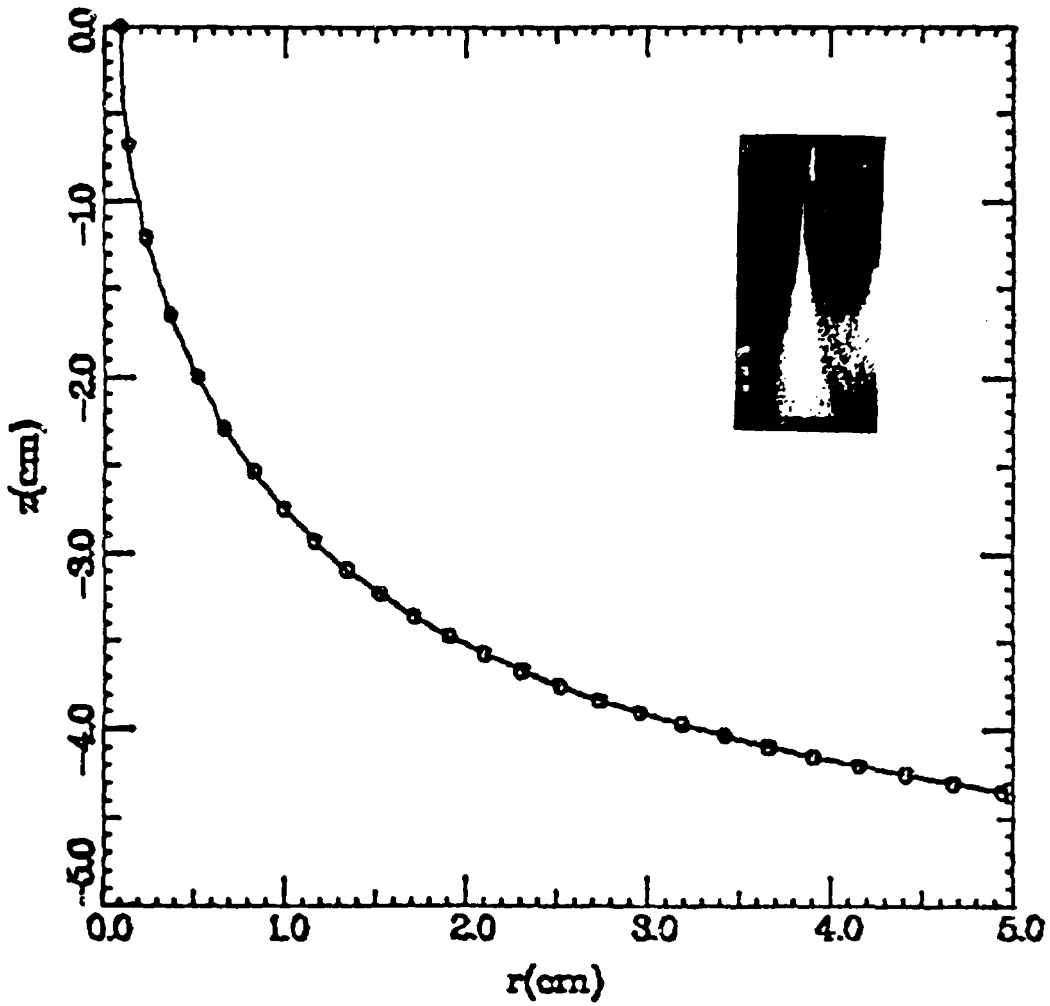


CHARACTERISTICS

- Compact
- Rugged
- Low Power Input Requirements
- Deep Throttle Capability
- Auto-Dispersal or Spray Droplets
- 10 to 100μm Droplet Size Range
- Drop Size Insensitive to Fluid Properties

Figure 1

ELECTROSTATIC SPRAY PLUME PROFILE



R_{max}	112	μm
dQ/dt	0.60	ml/sec
ρ_e	1.950	C/m^3
D_{mmd}	60.0	μm
R_0	0.9	mm
V_L	7700	V
Z_L	20.0	cm
ρ_f	845	kg/m^3
ρ_a	1.00	kg/m^3
μ_a	1.90 (-5)	kg/m-sec
τ	0.500	msec

Figure 2

Wednesday AM Session

8:30 Morning Chairman

C. Martel
AF Engineering Service Center/Tyndall AFB Florida

8:35 Air Force 10 Year Plan and Associated Activities

Maj. B. Lenz
ODCS (Logistics & Engineering)/Pentagon

9:00 Navy Mobility Fuel Research and Development Program

A. Roberts
Naval Material Command/Energy and Natural Resources Division

9:25 Air Force Research and Development Programs and Future Requirements in Non-Mobility (Facility) Energy Technology

S. Hathaway
AF Engineering Services Center/Tyndall AFB Florida

9:50 Research in Energy Conservation in the DOE Energy Conservation Program

K. Bastress
Department of Energy
Energy Conservation and Utilization Technology Division

10:15 BREAK

10:30 Use of Alternate Fuels in Commercial Turbines and Boilers and Applications to Air Force Problems

J. Kliegel & R. Thompson
KVB - Research Cottrell

10:55 AFESC Supported Research and Needs Associated with Gas Turbine Engine Emissions and Other Combustion Related Problems

Capts. T. Slankas & H. Clewell
AF Engineering Services Center/Tyndall AFB Florida

11:20 Status of the Utilization of New and Alternative Fuels in Airbreathing Turbine and Ramjet Engines

C. Martel, C. Delaney, J. McCoy & Capt. Potter
Aero Propulsion Laboratory
Wright Aeronautical Laboratories (AFWAL)

11:55 LUNCH

AIR FORCE ENERGY PROGRAM

The Air Force Energy Office (HQ USAF/LEYSF) has overall responsibility for energy conservation and energy programs. This involves acting as a focal point for energy policy developed by DOD and DOE, developing energy policy for Air Force major commands and separate operating agencies and tracking energy consumption data Air Force wide. Air Force energy consumption has been reduced in FY 81 as follows:

Aircraft Operations 14 percent from FY 75
Vehicles Operations 12 percent from FY 79
Facility Operations 14 percent from FY 75

Energy goals for FY 82 are as follows:

Aviation fuels no growth from FY 75 consumption

Motor fuel no growth from FY 80 consumption

Facility operations 14 percent reduction from FY 75 consumption

Diesel fuel zero growth from FY 80 consumption with diesel and motor gasoline consumption combined.

DOD has established additional energy goals as follows:

Goal	AF Status FY 81
Gasohol 25 percent of unleaded fuel by FY 85	1.5%
Coal usage of 10 percent by FY 85	6.5%
Alternate energy sources (solar, RDF) 1% by FY 85	.06%
Improve aggregate fuel efficiency of operational equipment 5% by FY 1990	

Maj Brian Lenz
Hq USAF/LEYSF
6 Oct 81

NAVY MOBILITY FUEL RESEARCH AND DEVELOPMENT PROGRAM

Dr. A. Roberts
Naval Material Command (MAT08E)
Washington D.C.
(202/692-1444)

ABSTRACT NOT AVAILABLE

AIR FORCE RESEARCH AND DEVELOPMENT PROGRAMS AND FUTURE REQUIREMENTS IN NON-MOBILITY (FACILITY) ENERGY TECHNOLOGY

S. Hathaway
AF Enginering Services Center/Tendall AFB Florida
(AUTO-970-4114, 904/283-4111)

ABSTRACT NOT AVAILABLE

OVERVIEW OF RESEARCH IN ENERGY CONVERSION IN THE DOE ENERGY CONSERVATION PROGRAMS

E. Karl Bastress, Director
Energy Conversion and Utilization Technologies Division
Office of Energy Systems Research
Conservation and Renewable Energy
U.S. Department of Energy

ABSTRACT

The DOE Energy Conversion and Utilization Technologies (ECUT) Program was established in FY 1981 under the Assistant Secretary for Conservation and Renewable Energy to provide a technology base activity in support of the DOE programs in energy conservation. The ECUT program constitutes a focal point for research on advanced energy conversion concepts and efficient energy utilization processes. This presentation is limited to a discussion of research in energy conversion in the ECUT Program.

The overall goals of the ECUT Program are to:

- o Expand the technology base available to the private sector for development of improved energy systems and devices; and
- o Evaluate new or innovative concepts for improved efficiency or alternative fuel use in energy conversion systems or utilization devices.

ECUT Program goals are achieved through Federal support of research in high-risk, long-range areas where the private sector investment is limited. Implementing this strategy has involved a sequence of steps. First, advanced technology needs were identified after intensive study of energy conversion losses and energy uses in the U.S. Then, advanced technology concepts with potential for improving energy productiity or efficiency, or for increasing the use of alternative fuels, were identified, evaluated, and ranked according to their relevance to technology needs and program goals and objectives. Finally, program plans for developing selected concepts were formulated.

The ECUT program is a cooperative endeavor by government, the academic community, national laboratories, and industry. This cooperation affords considerable opportunity for interdisciplinary review of technology needs and definition of problems requiring solutions and for ready transfer of task results to end-use sectors. Periodically, joint conferences are sponsored to share results and to plan future activities.

The Energy Conversion Technology Program element addresses the specific problems associated with the efficiency limits and multi-fuel use capability of components and/or systems used in the conversion of energy applicable to all energy-use sectors. The complete range of energy conversion is considered through efforts in three Major Activities: (1) Engine Combustion Technology; (2) Closed-Cycle Power Systems; and, (3) Direct Heating an Conversion Systems.

Engine Combustion Technology

The Engine Combustion Technology Activity supports the development of improved piston engine technology through the development of advanced instrumentation and analysis methods for combustion processes, and the application of these methods to performance analyses of innovative Otto cycle and diesel cycle engine combustion systems. This activity is conducted in close cooperation with U.S. engine manufacturers. Cooperative working groups composed of participants from universities, DOE laboratories, private research organizations, and the engine manufacturing industries are studying homogeneous-charge engines, light-duty diesels, and direct-injection stratified charge engines. The technologies used in the project include laser-based measurement techniques and large-scale multidimensional computer solutions of the physical and chemical equations that describe the fluid mechanics and combustion chemistry of engine operation. The technical objective of this activity is to improve piston engine efficiency by developing the analytical capability to understand the mechanisms associated with throttling losses, pumping losses, lean limits of operation, and efficiency penalties associated with emission controls.

Closed-Cycle Power Systems

The Closed-Cycle Power Systems Activity focuses on the development of the technology base required to resolve technical problems that limit the performance, reliability annd availability of such closed-cycle concepts as Stirling engine technology, Rankine/Brayton cycle technology, and other advanced concepts for closed-cycle power systems for heat engines and heat pumps. This activity supports the evaluation of new components and systems applicable to both stationary and mobile power systems and is conducted by U.S. industrial firms active in closed-cycle system development. The activity seeks and exploits research opportunities that make such systems and components more efficient and capable of alternative fuels use. Primary emphasis is directed to enhancement of the technology base required to understand the fundamental nature and technical characteristics of innovative concepts of Stirling cycle technology. Activities focus on the development of free-piston Stirling engines, kinematic Stirling engines, and component analyses appropriate to each. Limited activities will focus on the generation of technology base information relevant to the successful development of advanced Rankine and Brayton cycle as well as other advanced concepts of closed cycle technology.

Direct Heating and Conversion Systems

The Direct Heating and Conversion Systems Activity supports exploratory development of new technologies that can improve the performance and fuel flexibility of furnaces, boilers, and advanced direct energy conversion systems. Emphasis is directed to the development of data and design methods for furnaces and boilers, the investigation of advanced concepts for efficient use of "dirty" fuels, examination of retrofit possibilities of furnace and boiler systems to use non-petroleum type fuels, and the development of direct energy conversion options for enhancing cogeneration. Activities are conducted by representatives of academia, industry, and government laboratories.

USE OF ALTERNATIVE FUELS IN COMMERCIAL TURBINES AND BOILERS AND APPLICATIONS TO AIR FORCE PROBLEMS

J. Kliegel, R. Thompson, and A. M. Mellor

KVB, Inc.

Both shale- and coal-derived liquid fuels have been considered as alternatives for aircraft and stationary gas turbine engines. It is generally agreed that shale fuels make more suitable aircraft fuels than coal fuels, and shale fuels made to aircraft specifications (particularly JFTOT) pose no combustion difficulties.

In contrast, minimally processed coal liquids are the most inexpensive fuels based upon coal resources, and it is desirable to examine their potential utilization in non-aircraft gas turbines. A recent DOE-funded program at Purdue University has burned SRC-II middle distillate and blends of this fuel with Jet A in simplified gas turbine configurations to examine this possibility. Selected performance results will be presented.

The application of alternative fuels in boilers has progressed from the laboratory combustion characterization phase into the short term full-scale trial demonstration phase for some alternative or synthetic fuels. For example, solvent refined coal (both solid and liquid), coal-oil slurries, waste lubricants and organics, and refuse derived fuels have been fired in industrial or utility size units. However, long term operating effects have not been established because of the limited availability of fuel in many cases. Also, the conversion potential of a wide variety of boilers to alternative fuels is still primarily in the study phase, although comparison of cost estimates with actual cost should occur in the next 1-2 year period as more conversions are implemented.

As synthetic fuel production processes are modified to optimize product yield and process economics, fuel compositions have changed resulting in further fuels combustion characterization at the laboratory scale. Further

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research work is continuing, particularly for low-NO_x modified combustion modes, to examine the soot formation and smoking tendency for some synthetic fuels.

This paper will summarize the recent applications experience of alternative fuels in boilers, recent development problems, on-going combustion characterization efforts, and issues of interest in applying these fuels specifically to Air Force boilers and other combustion equipment.

AFESC SUPPORTED RESEARCH AND NEEDS ASSOCIATED WITH GAS TURBINE ENGINE EMISSIONS AND OTHER COMBUSTION RELATED PROBLEMS

Capts. T. Slankas & H. Clewell
AF Engineering Services Center/Tendall AFB Flordia

ABSTRACT NOT AVAILABLE

USE OF NEW AND ALTERNATIVE FUELS IN AIR-BREATHING GAS TURBINE AND RAMJET ENGINES*

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The Fuels Branch of the Aero Propulsion Laboratory is actively involved in fuels combustion research and development and related combustion programs. The fuels Branch is responsible for the research, development, and field support of aviation turbine and ramjet fuels for the Air Force. This responsibility has led to our involvement in the following programs, each to be discussed separately: (a) use of fuels from alternative sources for conventional aircraft; (b) development and use of special high energy fuels for air-breathing missiles; and (c) fuel combustion research, combustion modeling, and combustion diagnostics (this latter work to be discussed in a separate presentation by Mr Royce P. Bradley).

Alternative Fuels. As light, high-quality petroleum crude oils decrease in availability, aviation turbine fuels will increasingly be produced from heavy, sour crudes, oil shale, tar sands, coal, and possibly biomass. The ultimate objective of an advanced development program is to formulate an aviation turbine fuel specification that assures that any fuel meeting the specification will be completely suitable for use, regardless of origin and refining processes used. To prepare this ultimate specification, the combustion performance of fuels must be known. To this end, a wide range of fuels, including fuels blended to simulate products derived from shale, tar sands, and coal, have been tested in combustors representing the J-57/TF-33, J-79, J-85, TF-41, F-100, and F-101 engines. Augmentor tests for the J-79, J-85, TF-30, and F-100 have also be initiated.

The tests with the wide spectrum of fuels and different engine combustors have provided needed information as to how different fuel properties and compositions affect the performance and durability of the combustors tested. Current combustor modeling and correlation capabilities do not allow the accurate extrapolation of these data to other engine combustors. Therefore, contracts were recently awarded to Purdue University's School of Mechanical Engineering and to Pratt and Whitney Aircraft Division to develop correlations and models to predict fuel effects on turbine engine combustors and hot section components. The fuel effects programs mentioned above will provide the data base. The successful completion of these programs will eliminate much of the testing that will otherwise be required to qualify new fuels for aircraft turbine engine use. These correlations and models will also be used in specifying minimal acceptable combustion performance for the "ultimate" fuel specification mentioned above.

In 1982 and 1983 one or two engine types are to undergo qualification testing with JP-4 produced from oil shale. This will be followed by the operational use of shale JP-4 in late 1983 or early 1984 at one or two western Air Force bases. The fuel for these programs will be provided as part of the recently signed price guarantee agreement between the Department of Energy and the Union Oil Company.

Alternative Fuels Research Needs

a. Better understanding of soot formation within combustors; the effects of fuel composition, combustor design, and operating conditions.

b. Improved combustion models that can predict fuel effects on combustor discharge temperature patterns.

Missile Fuels. The range of air-breathing cruise missiles such as the Air Force's AGM-86B Air Launched Cruise Missile (ALCM) and the Navy's BGM-109 Tomahawk is limited by the volume of fuel that can be carried. The Fuels Branch has developed special high-density liquid hydrocarbon fuels to extend the range of volume-limited missiles such as the ALCM. By using JP-10, the ALCM will have about 15 percent more range than if JP-4 were used. To further increase the volumetric energy content of fuels, we have initiated work to develop carbon slurry fuels for turbine engines. (Carbon slurry is actually a misnomer; these fuels consist of a stabilized suspension of submicronic carbon particles in a liquid hydrocarbon fuel).

Carbon slurry fuels for turbine powered missiles appear to be feasible and promise about a 25 to 30 percent increase in volumetric heat of combustion as compared to JP-10. Experimental carbon slurry fuels have been produced by Ashland Chemical Company, Suntech Corporation, and Exxon Research and Engineering Company. The formulation problems require a suitable compromise among the conflicting requirements of: (1) long storage stability; (2) low viscosity at -65°F; (3) high energy content per unit volume (i.e., high carbon loading), and (4) good combustion characteristics. Major variables include carbon particle type, size distribution, and loading, the type and amount of surfactant or gelling agent used to obtain acceptable storage stability, and the choice of carrier liquid.

Dr G. M. Faeth of Pennsylvania State University has studied the combustion of single droplets of carbon slurry fuels. He describes the combustion process as occurring in several stages: (1) droplet heat-up; (2) evaporation of the liquid from the slurry droplet, leaving an agglomerate of the carbon particles; (3) heat-up of the solid agglomerate; and (4) combustion (or quenching) of the solid phase. This latter step, the combustion of the solid phase, takes much more time than the other three steps and controls the rate of combustion obtainable.

The Garrett Corporation has demonstrated that carbon slurry fuels can be burned in gas turbine combustors, but that excessively long residence times are required.

A contract was recently awarded to the Suntech Corporation with subcontractors Williams International and General Electric Company. This program will develop improved carbon slurry fuels and demonstrate the combustion performance of these fuels. Lessons learned will be applied to new slurry fuel formulations in an iterative manner. Another new program, sponsored by the Turbine Division of the Aero Propulsion Laboratory, will develop a combustor for carbon slurry fuels. A small combustion research program, to be sponsored by the Fuels Branch, is scheduled for FY82.

The use of boron slurry fuels in turbine engines is being investigated by the Garrett Corporation, with subcontractor Atlantic Research Corporation, under a Defense Advanced Research Projects Agency (DARPA) funded program. This program, nearing completion, is managed by the Aero Propulsion Laboratory. A separate program sponsored by the Ramjet Division of the Aero Propulsion Laboratory is to develop a ramjet combustor for boron slurry fuels. Atlantic Research Corporation is the contractor.

Missile Fuels Research Needs

a. Understanding of carbon particle combustion, effects of carbon particle structure and method of production, and the selection of catalysts.

b. Methods to eliminate or prevent the agglomeration of the individual carbon particles into larger clumps (i.e., agglomerates) that greatly increase the combustion time.

c. Improved injection and atomization methods for slurry fuels.

d. Methods to obtain high combustion efficiency for slurry fuels in combustors of reasonable size.

e. Methods to prevent or counter the deposition of boron oxides on turbine blades and other hot section components.

Wednesday PM Session

1:30 Afternoon Chairman

Capt. T. Slankas
AF Engineering Services Center/Tyndall AFB Florida

1:35 Propulsion, Oxidation and Reaction Kinetics of Hydrocarbons and Alternative Fuels

I. Glassman & F. Dryer
Princeton University

2:00 Ionic Mechanisms of Carbon Formation in Flames

H.F. Calcote
Aerochem Research Laboratories, Inc.

2:25 Mechanisms of Exhaust Pollutant and Plume Formation in Continuous Combustion

G.S. Samuelson
University of California - Irvine

2:50 Hydrocarbon Droplet and Particulate Formation, Combustion and Extinction Phenomena in Turbulent Reacting Flows

F.A. Williams
University of California - La Jolla/Princeton University

3:15 BREAK

3:30 Single Droplet Combustion Studies of Carbon Slurry Fuels

G.M. Faeth
Pennsylvania State University

3:55 Thermodynamics of Organic Compounds

W.D. Good
DOE Bartlesville Energy Technology Center

4:20 Gas Interaction and Liquid Phase Reactions Associated with Swirl Combustion and Explosions

P. R. Choudhury & M. Gerstein
University of Southern California, Los Angeles

4:55 ADJOURN

7:00 SOCIAL -- Surfside Holiday Inn

8:00 BANQUET -- Surfside Holiday Inn

Advanced Fuels Combustion Research

(AFOSR Contract No. F49620-78-C-0004)

Irvin Glassman, Frederick L. Dryer and Forman A. Williams
Principal Investigators

Department of Mechanical and Aerospace Engineering
Princeton University
Princeton, New Jersey 08544

In the coming decades fuel considerations for air breathing propulsion systems will be of prime importance to the Air Force. The currrent and proposed program concentrates on combustion associated problems of advanced fuels. Since gas turbine fuels of the future will contain larger and larger concentration of aromatics, the possibility of soot and coke formation affecting gas turbine combustor can and turbine blade lifetime becomes of crucial concern and has been the focus of the current Princeton AFOSR effort. Similarily, in the realm of ramjet and other ducted systems, slurried fuels containing boron or carbon afford theoretical improvements in performance significant enough to warrant serious consideration of their combustion difficulties, thus studies of these advanced fuels are to be integrated into the present program.

Specifically the ongoing effort studies the oxidation kinetics of aromatics (benzene, alkylated benzenes and polycyclic aromatics) by use of the turbulent flow reactor shown in Figure 1. The objectives are to provide understanding of soot formation processes, interactive effects in slurried fuel combustion and basic mechanisms for combustor modellers of aircraft gas turbine processes. Another aspect of the program tackles the problem of soot formation and destruction in pre-mixed and diffusion flame pockets such as those which exist in gas-turbine combustors. The results sought are a fundamental understanding of the soot process and the effect of physical (temperature, flow conditions, etc.) and chemical (fuel structure, additives, etc.) factors on the process. The experimental approach deals with accurate control of simple concentric diffusion and pre-mixed flame configurations in which the flame temperatures are controlled by inert gas addition to the vaporized fuels.

Extensive results have been obtained in both phases of the program, have recently been reported (Refs. 1-7) and are summarized as follows. In the oxidation of toluene, the first major intermediate formed is benzaldehyde, which decays either to the phenyl and formyl radicals or to benzene and CO. Ethyl benzene oxidation proceeds through styrene, which appears to react with H radicals to eventually form benzene and a vinyl radical. The initiation step in benzene oxidation forms the phenyl radical, which we have discovered starts the major chain branching step. Thus the results indicate that the study of all the alkylated benzene compounds, and benzene itself, should focus on the oxidation of the phenyl radical. Figure 2 reports benzene oxidation results and is representative of the extensive data (2) obtained on all aromatics tested to date. These results have led us to propose one of the first high temperature mechanistic routes for the oxidation of aromatic fuels (2,3). Observing the sequence of peaks of the intermediates shown in Figure 2, the oxidation process is begun at the phenyl ($+O_2$) stage by an exothermic chain branching reaction to form the phe-

noxy radical and an oxygen atom. The phenoxy appears as phenol due to reaction in the probe. The phenoxy isomerizes into the ketocyclohexadienyl radical, which expells CO and forms a cyclopentadienyl radical. Again, this latter radical appears as cyclopentadiene in Figure 2 due to probe reactions. The radical actually reacts with O_2 in a manner analogous to phenyl and forms a compound which due to resulting delocalization of the electron forms a ketone radical. The stable form of this radical is 2 cyclopentene-1-one and has been found in trace amounts in a mass spectroscopic examination of the reaction products. The radical is expected to once again follow the ring rupture step of CO expulsion and this time to form a butadiene radical. The butadiene radical undergoes pyrolysis to form vinyl acetylene, acetylene and ethylene and addition to form butadiene. Notice the sequence of peaks in Figure 2 is phenol, cyclpentadiene and almost simultaneously vinyl acetylene, butadiene, acetylene and ethylene. These results are significant with suspect to soot formation in that the oxidation intermediates of aromatics may be as significant to soot formation by aromatic fuels as the aromatic itself. We had earlier (4) suggested the possible importance of vinyl acetylene and butadiene in soot formation. More work is now underway with other aromatics and establishing the proposed mechanism with further experimentation and kinetic modelling.

Results from our soot program would lead us to believe that the dominant factors in soot formation in diffusion flames are the stoichiometric temperature of the fuel under the specific oxidizing condition and the actual fuel structure. Under pre-mixed conditions, particularly for aliphatic fuels, the flame temperature plays the dominant role and fuel structure is a factor, but a secondary one. For pre-mixed aliphatic flames, the higher the flame temperature the less the tendency to soot. As the temperature of the flame rises, the rate of oxidation of soot precursors becomes faster than the rate of precursor formation (9). The usual measure for the tendency of a fuel to soot under pre-mixed conditions is to determine at which equivalence ratio soot is first noticed - the larger the equivalence ratio the less the tendency to soot. This criterion establishs that acetylene should soot less than the olefins, which should soot less than the paraffins. This trend is contrary to what is known about the oxidation kinetics of the aliphatic fuels (8) and could be misleading under conditions which exist in aircraft gas turbines. Shown in Figure 3 are recent results (10) which compare the sooting equivalence ratio of ethane, ethylene and acetylene as a function of flame temperature. It is quite apparent that at low temperature all three fuels soot at the same equivalence ratio and at higher temperatures acetylene soots at leaner ratios than the other two. It is significant to note that ethane will not soot at any mixture ratio when the temperature is 2220 K or higher and acetylene when the temperature is 2420 K or higher. We believe these data show the dominant effect of temperature and the secondary effect of structure on sooting tendencies in pre-mixed aliphatic flames. Other aliphatic fuels and aromatics are to be investigated to support these hypotheses.

Much data on sooting in diffusion flames has been reported already (5,6). Figure 4 shows recent results of aromatics in comparison with these earlier aliphatic fuels. Plotted in this figure is the natural log of the reciprocal of the mass flow rate at the sooting height versus the reciprocal of

the stoichiometric temperature. At a given temperature, the higher the point on the graph the greater the tendency to soot. Thus one can come to many important conclusions with regard to diffusion flames based on these results: the higher the temperature the greater is the tendency to soot, the effect of fuel structure is important and various fuels should be compared at the same temperature, the C_4 and C_5 olefins and diolefins have the greatest tendency to soot among the aliphatics even acetylene and the aromatics soot much more readily than the diolefins contrary to other earlier work (11). The difference between the sooting tendency of the aromatics is small, but consistent with initiation kinetics we have observed in our studies of aromatic oxidation (2). Analysis of experimental diffusion flame data as reported in Figure 4 provides an excellent means of evaluating the effect of fuel structure and experimentation in this area will continue with more complex conjugated fuels as a means of determining structure effects and clues to the soot formation process.

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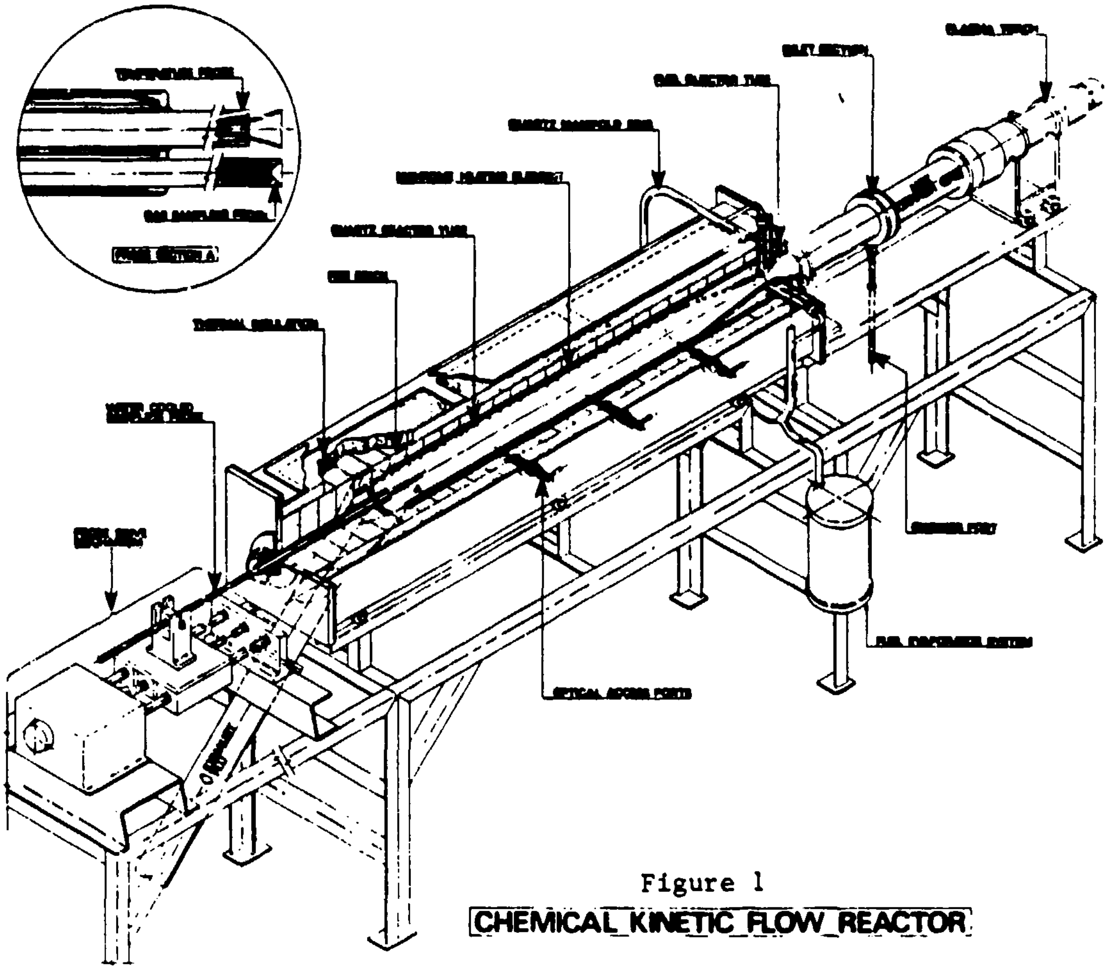
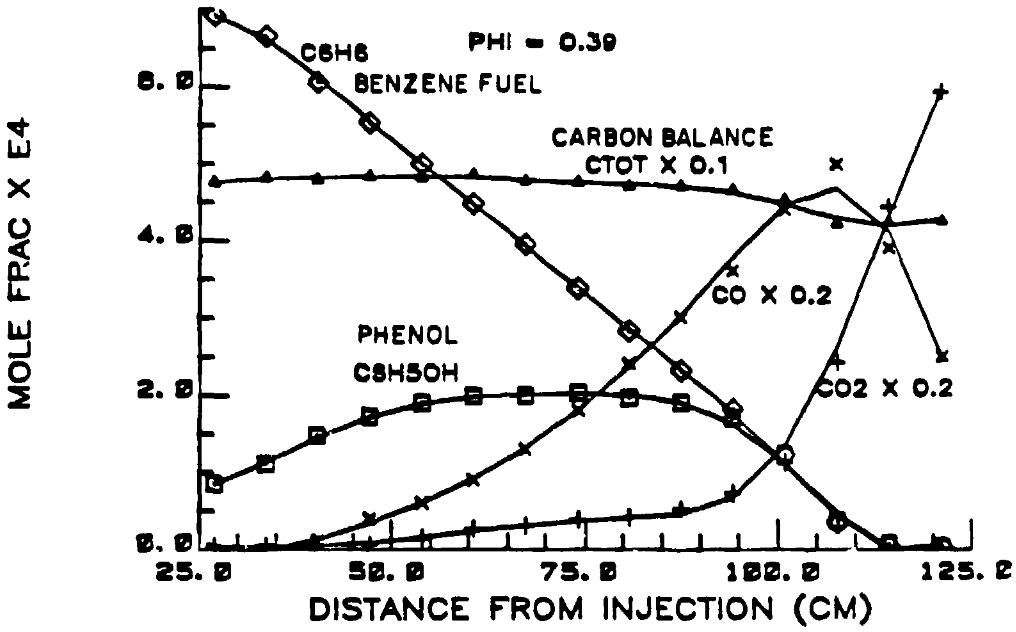


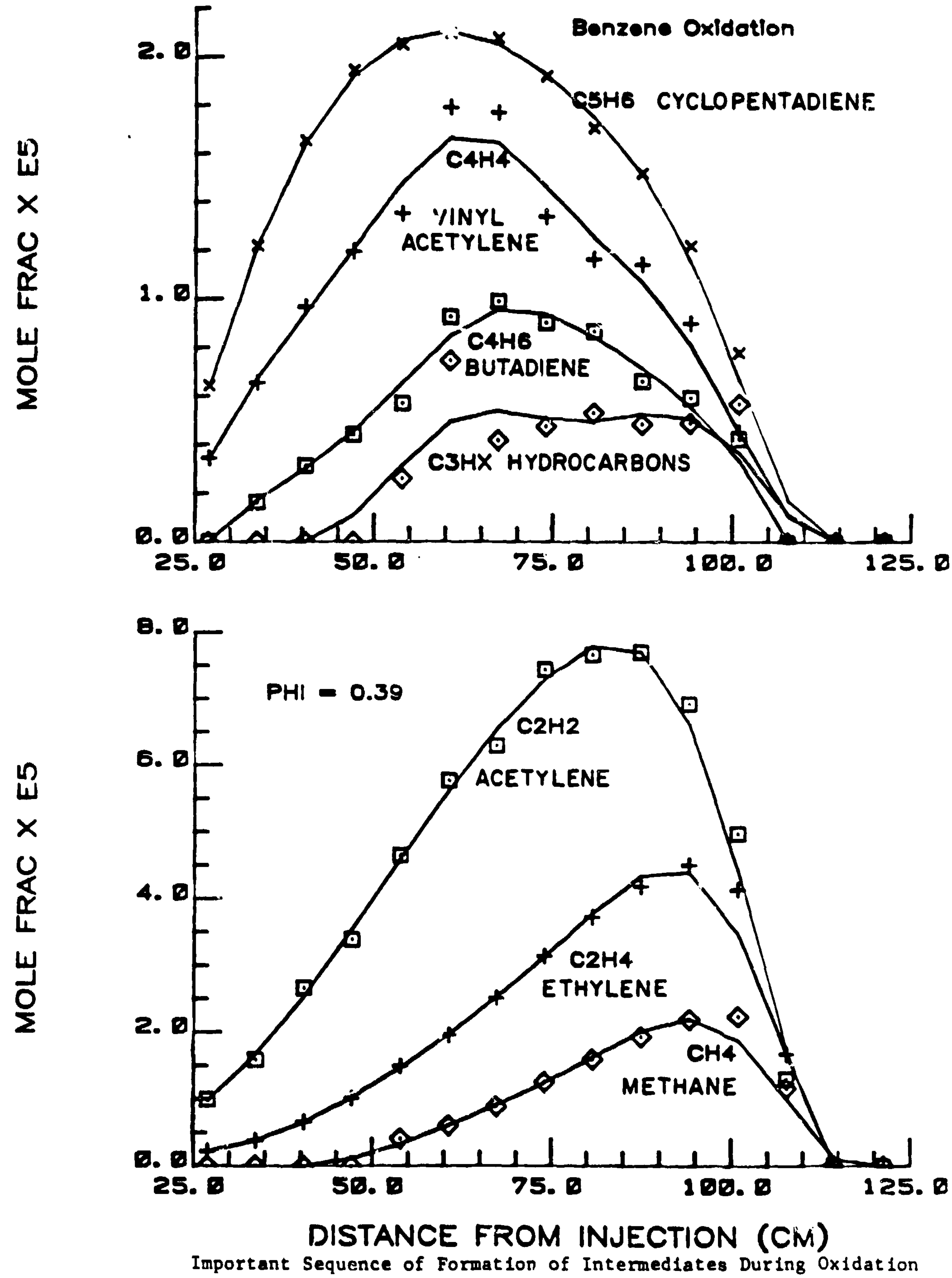
Figure 1

CHEMICAL KINETIC FLOW REACTOR



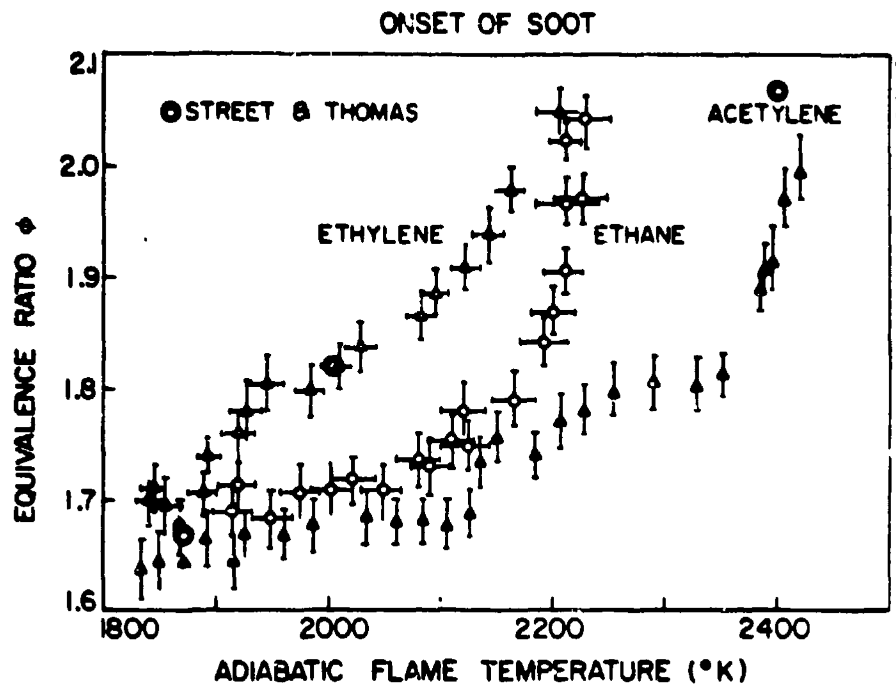
Fuel Consumption and Formation of Final Products in Benzene Oxidation at $\phi = 0.39$, $T \cong 1150$ K. Distance From Fuel Injection Point in Fig. 1.

Figure 2A



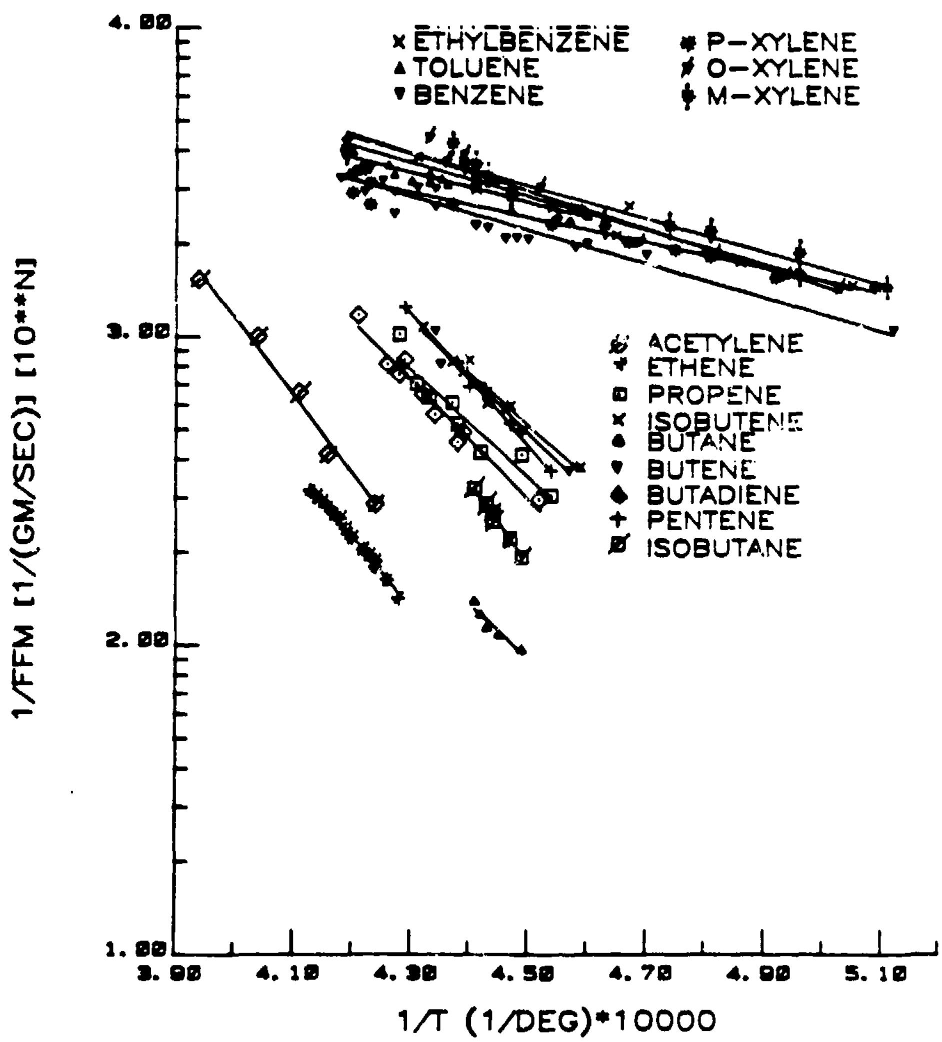
Important Sequence of Formation of Intermediates During Oxidation of Benzene. Same Conditions as Figure 2A.

Figure 2B



Sooting Φ as Function of Controlled T in Premixed Flames. Lower Φ's Greater Tendency to Soot at Fixed Temperature. Acetylene has Greatest Tendency to Soot Under Premixed Conditions.

Figure 3



Sooting in Diffusion Flames as Function of Temperature. Comparison Showing Aromatics Have Greater Tendency Than Aliphatic Fuels.

Figure 4

IONIC MECHANISMS OF SOOT FORMATION IN FLAMES

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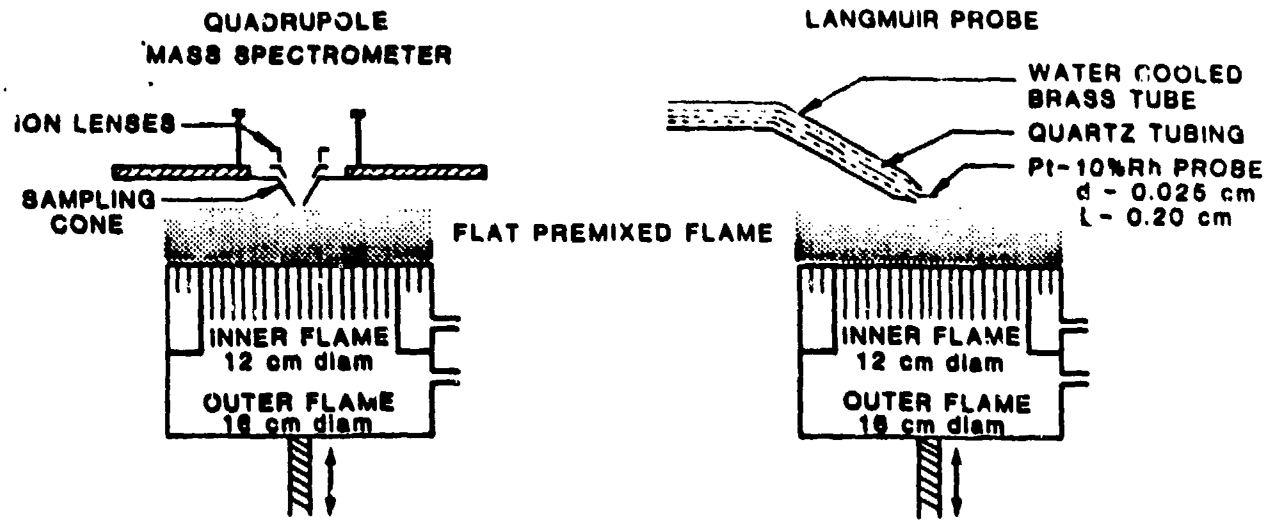
The objective of this program is to understand the mechanism of soot formation in flames and to interpret that mechanism in terms of the effect of synfuels on soot formation in air-breathing engines. This understanding will be used to suggest possible means of minimizing sooting in aircraft engines. The basic premise being examined is that chemi-ions are the precursors of soot nucleation and that the nucleation process involves a series of very fast ion-molecule reactions.

The technical approach is to make detailed studies of ion concentration and temperature profiles in low pressure flat flames to generate the experimental data necessary to quantitatively test our hypothesis. These studies, Figure 1, include mass spectrometric measurements of individual relative ion concentration profiles through the flame up to mass 5000 amu and Langmuir probe measurements of absolute total ion concentration profiles. An immediate objective is to convert the relative individual ion profiles to absolute ion concentration profiles. Some typical absolute total ion concentrations as a function of distance above the burner and equivalence ratio are presented in Figure 2. One of the interesting, unexplained observations is the appearance of two peaks in the profiles, the second peak dominating in sooting flames.

Simultaneously with the above fundamental mechanistic studies some empirical studies are in progress with the objective of giving more insight into the effect of synfuels on air-breathing engine performance. As a part of this effort a Threshold Soot Index, TSI, has been developed which makes it possible to compare data taken in different laboratories by different techniques or to convert all the data in the literature to one experimental system for comparison. This technique has been used to compare laboratory measurements of soot index with observations of smoke emission and flame radiation in jet engines and to consider the relationship between incipient soot formation and flame temperature, Figure 2. For the last comparison all of the premixed flame data in the literature was reduced to the critical equivalence ratio for soot formation on a specific burner. The adiabatic flame temperatures were then calculated at the critical equivalence ratio for each fuel. The trend in TSI with temperature, Figure 2, is generally positive when different temperatures are attained by varying the fuel structure, contrary to the effect of temperature on TSI when the temperature is varied by diluting the air/fuel mixture with nitrogen, as shown by the curve in Figure 2 for propane. We interpret these results as indicating a strong effect of both temperature and molecular structure on soot formation.



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- Flame Ion Mass Spectrometry of Individual Ion Profiles
- Langmuir Probe Measurement of Absolute Total Ion Concentration
- Thermocouple Measurement of Flame Temperature
- Adiabatic Flame Temperature Calculation
- Development of Threshold Soot Index (from Literature)
- Analysis of Soot Formation in Turbojet Engines (from Literature)

FIGURE 1 TECHNICAL APPROACH

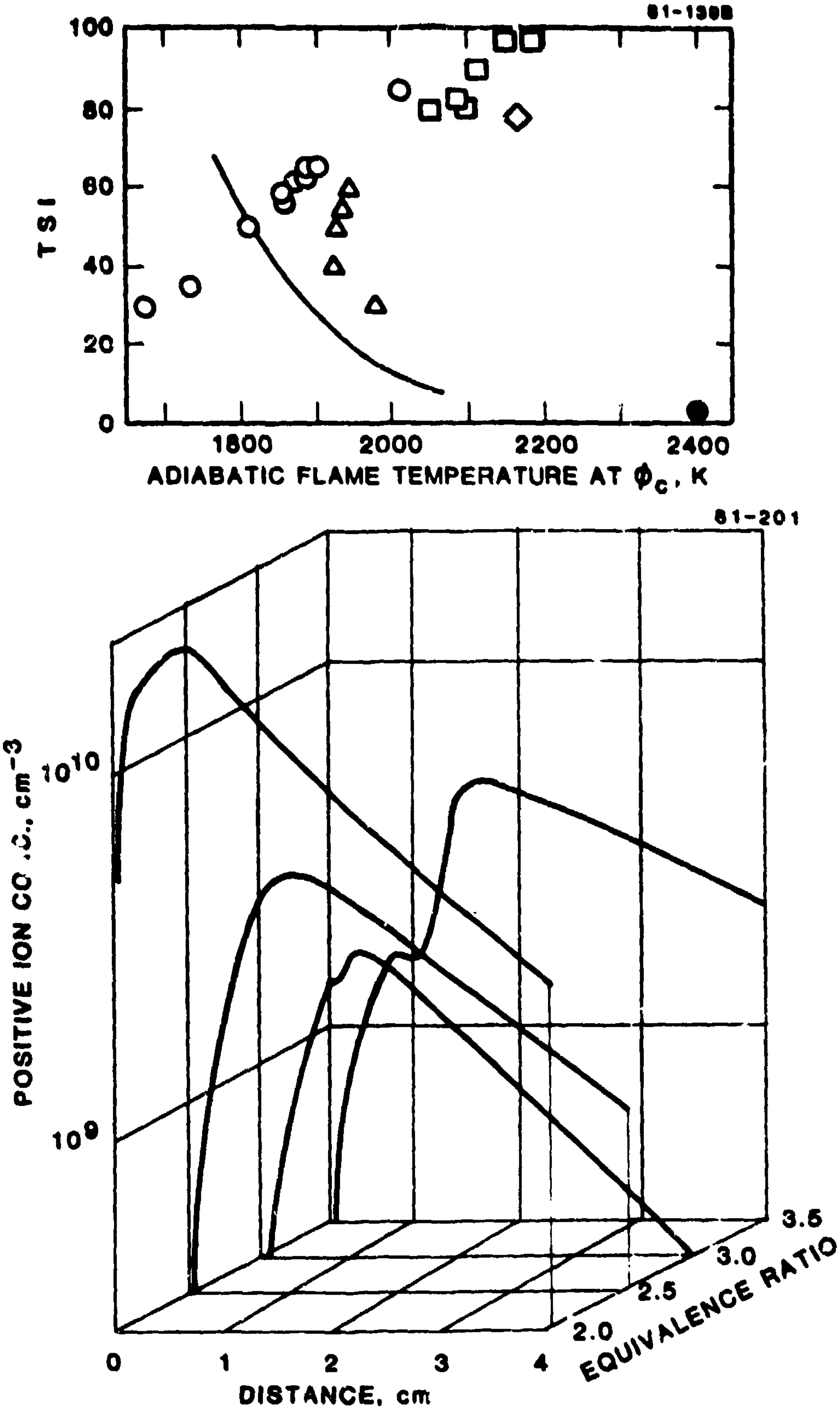

FIGURE 2 THE EFFECTS OF TEMPERATURE AND POSITIVE ION CONCENTRATION ON SOOT FORMATION IN FLAMES

MECHANISMS OF EXHAUST POLLUTANT AND PLUME FORMATION IN CONTINUOUS COMBUSTION

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The present analytical and experimental investigation is designed to clarify the relative influence of the mechanisms responsible for pollutant production in continuous combustion, evaluate predictive methods for characterizing complex flows, and assess experimental errors associated with sampling oxides of nitrogen. This information is necessary to establish guidelines and techniques for controlling gaseous pollutant and particulate production in present day and advanced jet engine combustors by control and modification of the combustion dynamic processes.

Studies are conducted utilizing experiments in nonreacting/reacting, swirling/non-swirling, and premixed/nonpremixed combustors under conditions simulating the basic flows characteristics of practical systems. Two-color laser anemometry is employed to measure simultaneously the two components of velocity and hence Reynolds stress. Dynamics of the combustion processes are addressed with high speed photography in combination with tracers to assess fuel jet penetration and subsequent mixing with the oxidant stream. Extractive probes are employed for gaseous species and particulate sampling, and GC/MS, atomic absorption, and CHN analyses are used for particulate composition. Fuels include both gases and liquids, the latter of which are introduced as prevaporized or liquid sprays. Techniques for in-situ measurement of droplet size and droplet velocity are being introduced for cold flow spray characterization and reacting flow droplet behavior.

During this period, seeding methods have been developed to (1) insure an equal density of seeds in both the main and jet flows, and (2) allow measurements under reacting conditions. Single component laser anemometry measurements of both the mean velocity and turbulence intensity have been conducted in two combustor configurations: opposed jet and centerbody. Emphasis has been directed to the periodicity of the flow, and the presence and impact of large scale structure on both the combustor performance and modeling. Flowfield data are provided to AFOSR contractors concerned with evaluating flow models, and are used by AFAPL staff to evaluate and understand centerbody performance. Further, AFESC/RDVC has contracted to fabricate a centerbody combustor system for fuels testing at Tyndall AFB, and an EPA contractor has utilized the opposed jet for catalytic combustor conditioning and preheat. In an AFESC/RDVC program, the centerbody has been employed to quantify the perturbation on local soot morphology, density, and size produced by a physical extractive probe in comparative measurements with a nonintrusive optical probe.

The sampling experiments have shown the presence of water to have little effect on the measurement of nitrogen oxides except in the presence of hydrocarbons. Tests with tubes of nickel and nickel alloys demonstrated that stainless steel is the least reactive of tube materials, other than quartz, for high temperature sampling. Tube wall temperatures should, however, not exceed 150°C.

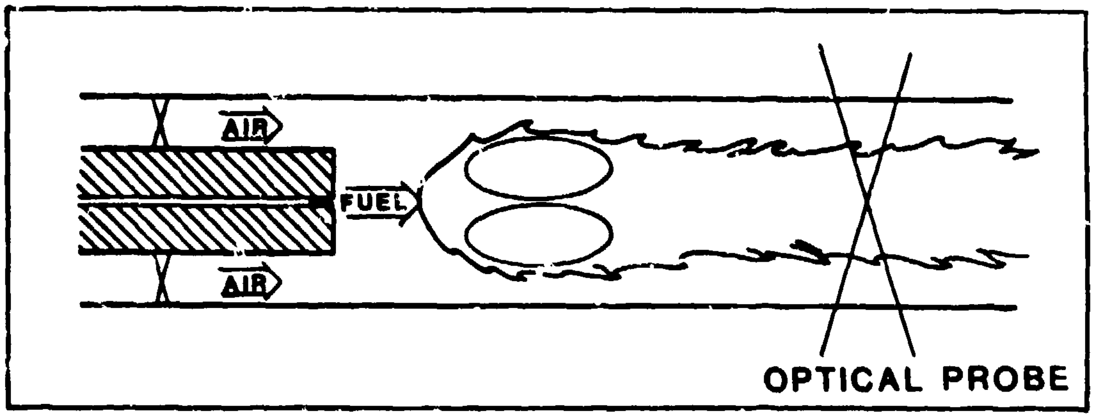
COMBUSTOR DYNAMICS

PROBLEM

- COMBUSTORS CHARACTERIZED BY COMPLEX (I.E., TURBULENT, RECIRCULATING FLOWS)
- PERFORMANCE, SOOT PRODUCTION REQUIRES IMPROVED UNDERSTANDING
- NON-INTRUSIVE DIAGNOSTICS IN INFANCY OF DEVELOPMENT
- MODELING LIMITED IN ABSENCE OF DETAILED INFORMATION

NEEDS

- MEASUREMENT OF FLUCTUATING PROPERTIES
- TESTS FOR PERIODICITY AND LARGE STRUCTURE
- DATA BASE
- COMMON TEST BEDS
  - MODEL VALIDATION
  - DIAGNOSTIC DEVELOPMENT
  - MODEL AND DIAGNOSTIC CALIBRATION
  - COMBUSTOR DYNAMICS STUDIES



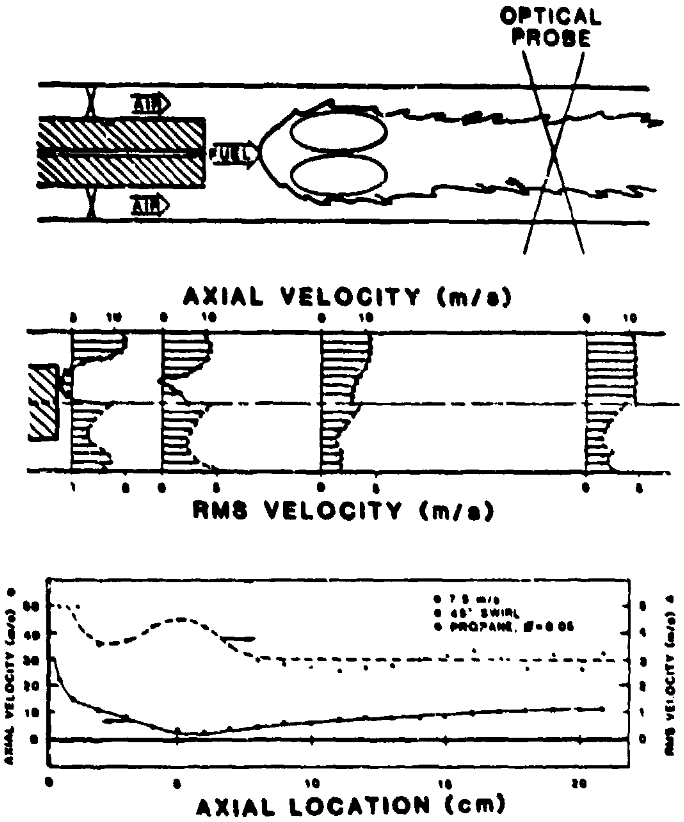
APPROACH

- OPTICAL DIAGNOSTICS (VELOCITY, REYNOLDS STRESS, SOOT, DROPLET SIZE/VELOCITY)
- SPATIALLY AND TEMPORALLY RESOLVED MEASUREMENTS
- STEPWISE INTRODUCTION OF COMPLEXITY (COLD, HEATED, HOT, FUEL SPRAY)
- TEST CANDIDATE CONFIGURATIONS

● TEST BED CRITERIA

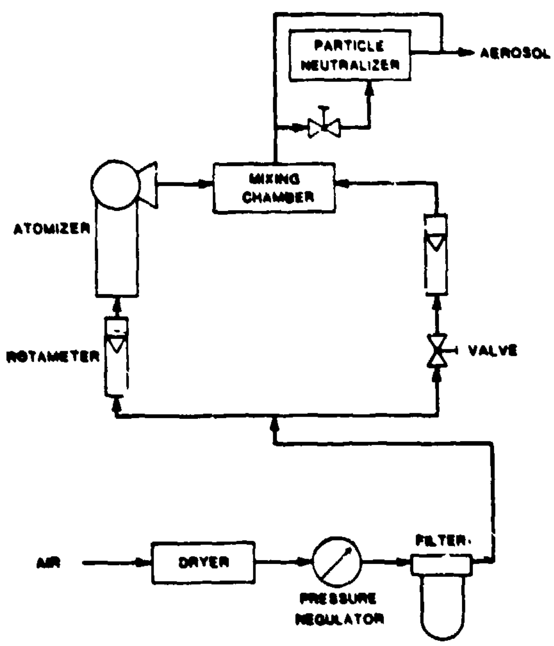
- STRONG BACKMIXING
- SWIRL
- AXISYMMETRIC
- CLEAN BOUNDARIES
- OPTICAL ACCESS
- AMEANABLE TO SPRAY INJECTION

● CANDIDATE GEOMETRY TEST



(BRUM, ET AL., 1981)

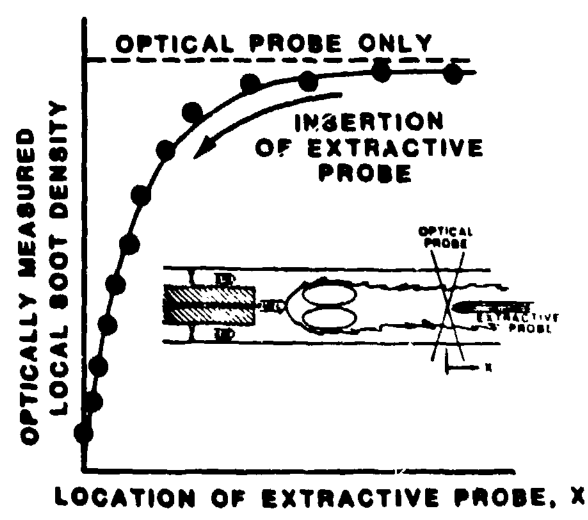
● MULTIPLE JET LA SEEDER



- 1μm ALUMINA
- UNIFORM CONCENTRATION
- STEADY FLUX

(IKIOKA, ET AL., 1981)

● SOOT PROBE PERTURBATION
(AFESC/RDVC PROGRAM)



(HACK, ET AL., 1981)

FUNDAMENTAL COMBUSTION STUDIES

RELATED TO AIR-BREATHING PROPULSION

F. A. Williams

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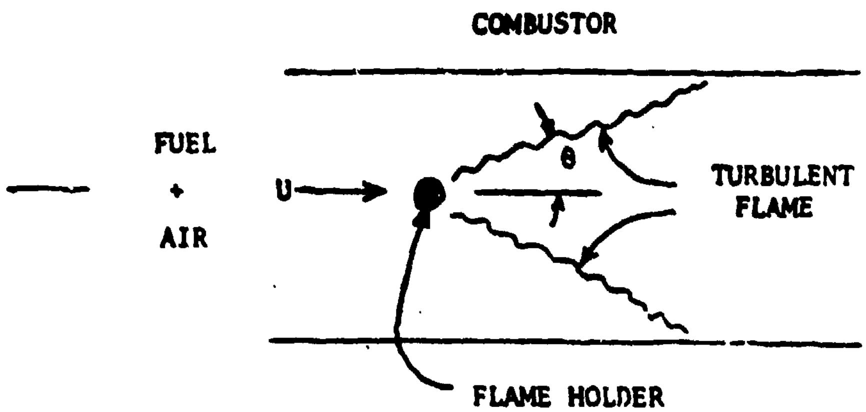
This research was directed toward developing basic information that is relevant to continuing problems in air-breathing combustion, specifically to improvement of efficiencies, to reduction of undesired emissions and to increase in accuracies of design methods. The most recent work has been focused mainly on turbulent combustion of gases. Specifically, new theoretical results have been obtained on turbulent flame speeds, which are useful in designing combustion chambers for maximum efficiencies, and new theoretical results have been obtained for lift-off and blow-off of turbulent diffusion flames, which are useful for calculating conditions needed for flame stabilization.

For turbulent diffusion flames, methods of accounting for effects of finite-rate chemistry were improved. It was concluded that differential diffusion of species has only a small effect on the use of particle seeding to measure mixture fraction but may produce a significant effect on NO formation. A method was devised for calculating quench, lift-off and blow-off conditions for turbulent diffusion flames, starting from first principles. It was found that for this purpose the only finite-rate reactions that need to be analyzed are those in the thin diffusion flemelets and the theory of conduction in randomly distributed networks is relevant.

In the area of premixed turbulent flames, influences of differing diffusivities for reactants and heat and influences of density changes across the reaction region were obtained by asymptotic methods. The approach is illustrated in Fig. 1. Flame speeds, flame structures and influences of the flame on the turbulence were calculated. An explanation was obtained for an experimentally observed anomaly at low frequencies in power spectra of velocity fluctuations in turbulent flames. The anomaly is illustrated in Fig. 2. The importance of the self-evolution behavior of wrinkled flames on turbulent flame dynamics was thereby established.

Research Sponsored Under AFOSR Grant 77-3362.



$\tan\theta = u_T/U$

First do singular expansion in β^{-1}

Carried to second order and gives linear stochastic problem

Next do regular expansion for small gradients

Carried to second or fourth order and gives flame speed

Get $\alpha = \int u \, d\tau = a/\delta$ in first approximation

$$\frac{u_T}{u_L} = \overline{\sqrt{1 + \left(\frac{\partial a}{\partial y}\right)^2 + \left(\frac{\partial a}{\partial z}\right)^2}} - \frac{\beta}{8}(L-1)\left[8 + \beta(L-1)\right]\delta^2\overline{\left(\frac{\partial u}{\partial x} - \underbrace{\frac{\partial^2 a}{\partial y^2} - \frac{\partial^2 a}{\partial z^2}}_{\text{CURVATURE}}\right)^2}$$

WRINKLING STRETCH

FIGURE 1. Theoretical Approach in Application of Asymptotic Methods to Turbulent Flame Theory and Resulting Flame-Speed Formula.

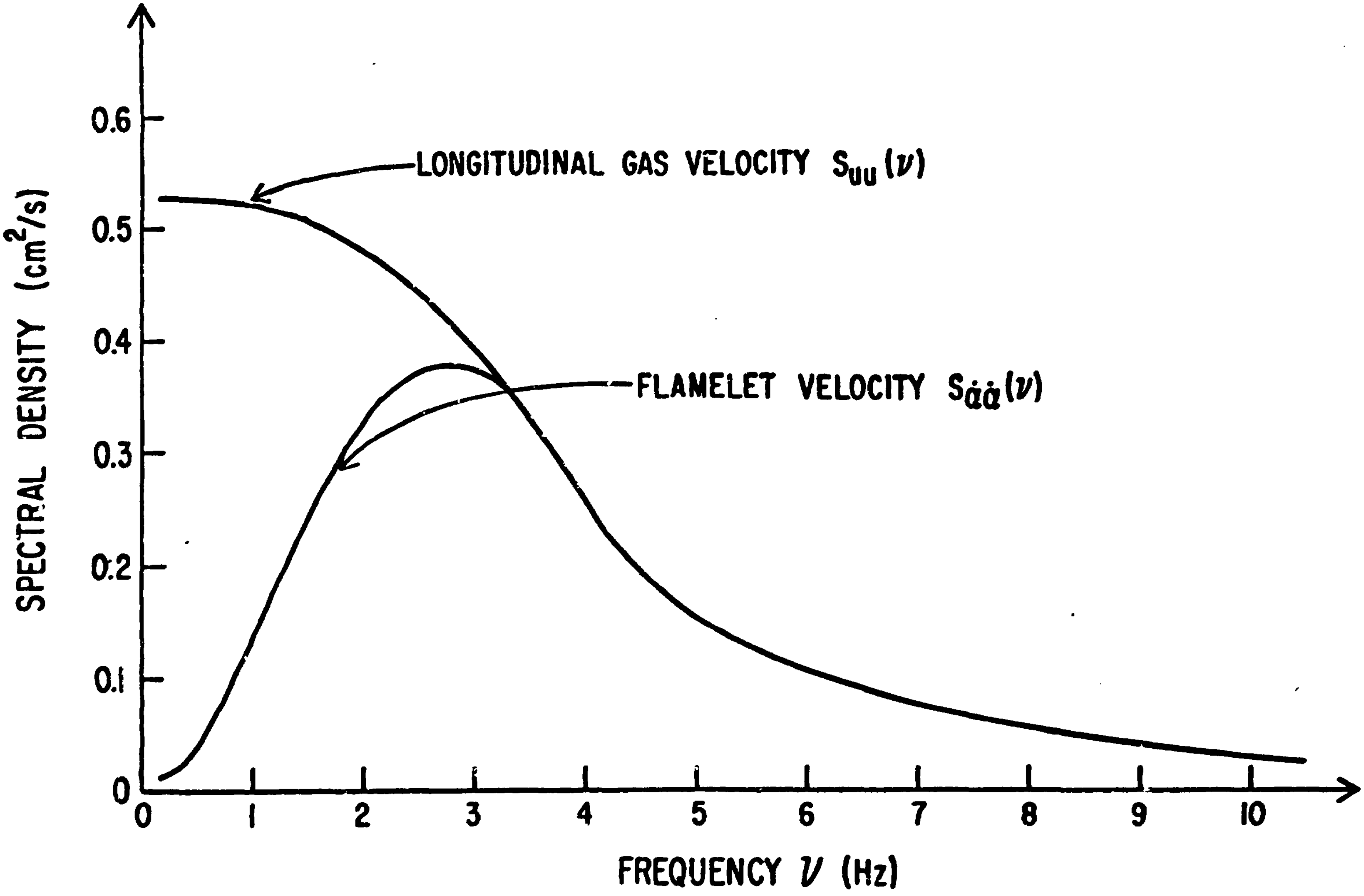


Figure 2. Representative Power Spectra for Gas and Flemelet Velocities, Illustrating Anomaly at Low Frequencies Explained by Self-Evolution of the Flame Front.

Single Droplet Combustion Studies of Carbon Slurry Fuels
(Contract F33615-81-K-2039)

G. M. Faeth, Principal Investigator
Department of Mechanical Engineering
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

Slurries, consisting of carbon black particles in a liquid hydrocarbon, provide a high volumetric energy density fuel which is attractive for volume-limited air breathing propulsion systems. Earlier investigations of the combustion of carbon slurry sprays in gas turbine combustors and well-stirred reactors indicate that carbon slurries require a greater combustor volume for good combustion efficiency than conventional liquid fuels, however, the mechanism and rates of combustion were not established.

The objective of research in this laboratory was to investigate the mechanism of carbon slurry combustion by studying individual drops. The approach involved observation of drop combustion in gaseous environments representative of combustion chamber conditions as well as developing a model of slurry drop combustion to aid in the interpretation of the measurements.

The first phase of the investigation involved observations of relatively large drops (400-1000 microns in diameter) supported at various positions in a turbulent diffusion flame whose structure was known (mean velocity, temperature and composition as well as turbulence intensities) [1-3]. It was found that carbon slurry combustion is a two-stage process, similar to the combustion of coal slurries. The liquid evaporates in a relatively short time, forming a porous agglomerate consisting of all the carbon particles originally in the slurry. The carbon agglomerate then heats-up and either reacts or is quenched depending upon the position in the flame. Even in regions of the flame where carbon reaction was a maximum, however, reaction of the carbon required 95% of the lifetime of the particle. A model was developed which provided good predictions of particle life histories for both phases over the test range (fuel equivalence ratios of 0.272-1.350) [1-3].

The current phase of the investigation consists of observations of slurry drop combustion for drop sizes more representative of practical combustors (10-100 microns in diameter). Experiments are being conducted with freely moving particles injected into the post-flame region of a laminar flat flame burner. A stream of carbon agglomerates is formed by drying monodisperse slurry drops produced with a Berglund-Liu aerosol generator and directing the particles along the centerline of the flat flame burner. Various gas mixtures are used in the burner to provide a range of fuel equivalence ratios and gas temperatures. Gas temperatures and composition are measured by fine wire thermocouples and isokinetic sampling coupled with gas chromatography. Gas and particle velocities are determined using laser Doppler anemometry. Agglomerate temperatures are found by optical pyrometry. Agglomerate mass and diameter are obtained by capturing the particles on a stainless steel filter within an isokinetic quenching probe.

Accumulation of data is in progress. However, for the results available thus far, the model was found to provide a fair prediction of the measurements [4]. The model tends to underestimate the rate of agglomerate reaction, however, since sub-surface reaction is more important for small particles. Measurements of particle density reveal a monotonic reduction of density with extent of reaction. This density reduction undoubtedly influences processes of pore diffusion as well as the dynamic and transport properties of the particle. It is apparent that more detailed consideration of subsurface processes will be required to achieve an adequate understanding of carbon agglomerate combustion.

References

1. Szkeley, G. A., Jr. and Faeth, G. M., "Combustion Properties of Carbon Slurry Drops in a Turbulent Diffusion Flame," AIAA Paper No. 81-0322, 1981.

2. Szekely, G. A., Jr. and Faeth, G. M., "Combustion Properties of Carbon Slurry Drops," submitted to AIAA J.

3. Szekely, G. A., Jr. and Faeth, G. M., "An Investigation of Slurry Fuel Combustion," AFWAL-TR-80-2125, January 1981.

4. Szekely, G. A., Jr. and Faeth, G. M., "Combustion of Carbon Slurry Agglomerates in a Laminar Premixed Flame," 1981 Fall Technical Meeting, Eastern Section of the Combustion Institute, Pittsburgh, October 1981.

THERMODYNAMICS OF ORGANIC COMPOUNDS

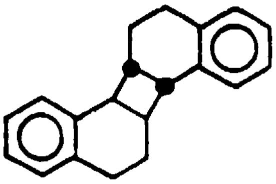
William D. Good and Norris K. Smith

U.S. Department of Energy
Bartlesville Energy Technology Center
Bartlesville, OK 74005-1398

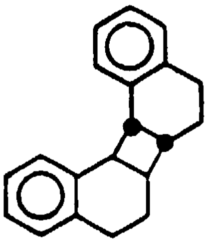
The purpose of this research program is to determine thermodynamic properties of currently used high density/high energy fuels, and of pure chemical compounds that may be constituents of high energy fuels of the future. In particular, enthalpies of combustion of pure compounds are measured to derive enthalpies of formation. Compounds with strained bridging bonds or with substituents that have steric interaction have been chosen for study. This information may be helpful in synthesizing organic molecules having high energy/volume or energy/mass ratios.

Figure 1 shows the formulas of some of the compounds that we have studied, and their enthalpies of formation. All values are in Kcal/mole.

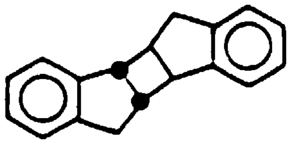
Figure 2 gives the detailed results obtained on heptacyclotetradecane, HCTD. This compound has an unusually high density of 1.26.



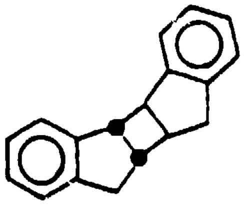
16.80 ± 0.64(c)



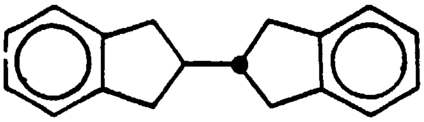
19.15 ± 0.43(c)



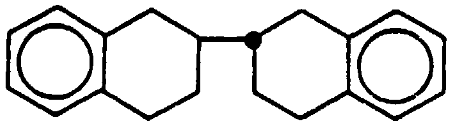
37.06 ± 0.44(c)



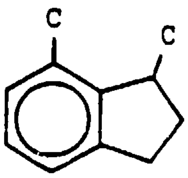
37.73 ± 0.80(c)



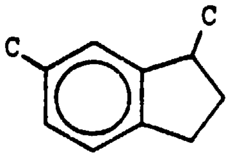
6.24 ± 0.56(c)



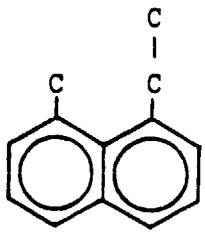
-11.38 ± 0.60(c)



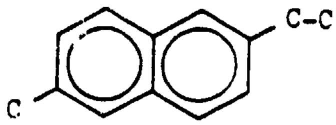
-13.20 ± 0.26(1)



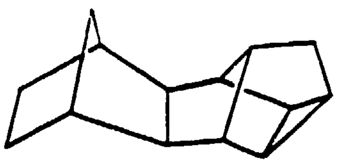
-12.86 ± 0.25(1)



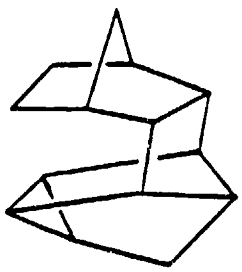
6.13 ± 0.30(1)



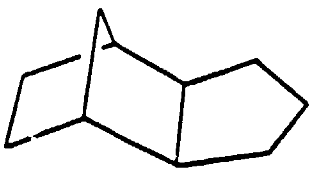
-7.18 ± 0.38(1)



9.34 ± 0.49(1)

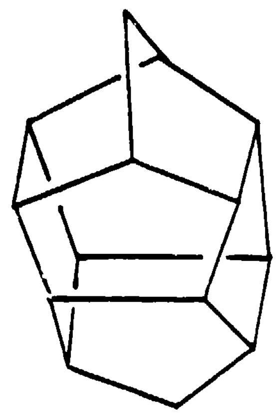


16.56 ± 0.40(1)



-29.29 ± 0.29(1)

FIGURE 1. Heats of formation, Kcal/mol.



HEPTACYCLOTETRADECANE

$C_{14}H_{16}(c) + 16\ O_2(g) = 14\ CO_2(g) + 8\ H_2O(l)$

$\Delta Ec°/M$ =	-10019.42	CAL/G
	-10020.00	
	-10020.47	
	-10019.35	
	-10019.68	
	-10019.50	
	-10019.20	
	-10019.79	
MEAN	-10019.68	CAL/G
STD. DEV. OF MEAN	±0.29	CAL/G
$\Delta Ec°$ =	-1846.46 ± 0.12	KCAL/MOL
$\Delta Hc°$ =	-1848.83 ± 0.12	KCAL/MOL
$\Delta Hf°$ =	-14.40 ± 0.30	KCAL/MOL
CO_2 RECOVERY	(99.90 ± 0.01)%	(MEAN AND SDM)

FIGURE 2

GAS INTERACTION AND LIQUID PHASE REACTIONS ASSOCIATED WITH SWIRL COMBUSTION AND EXPLOSIONS

AFOSR Grant 77-3354

P. Roy Choudhury and M. Gerstein

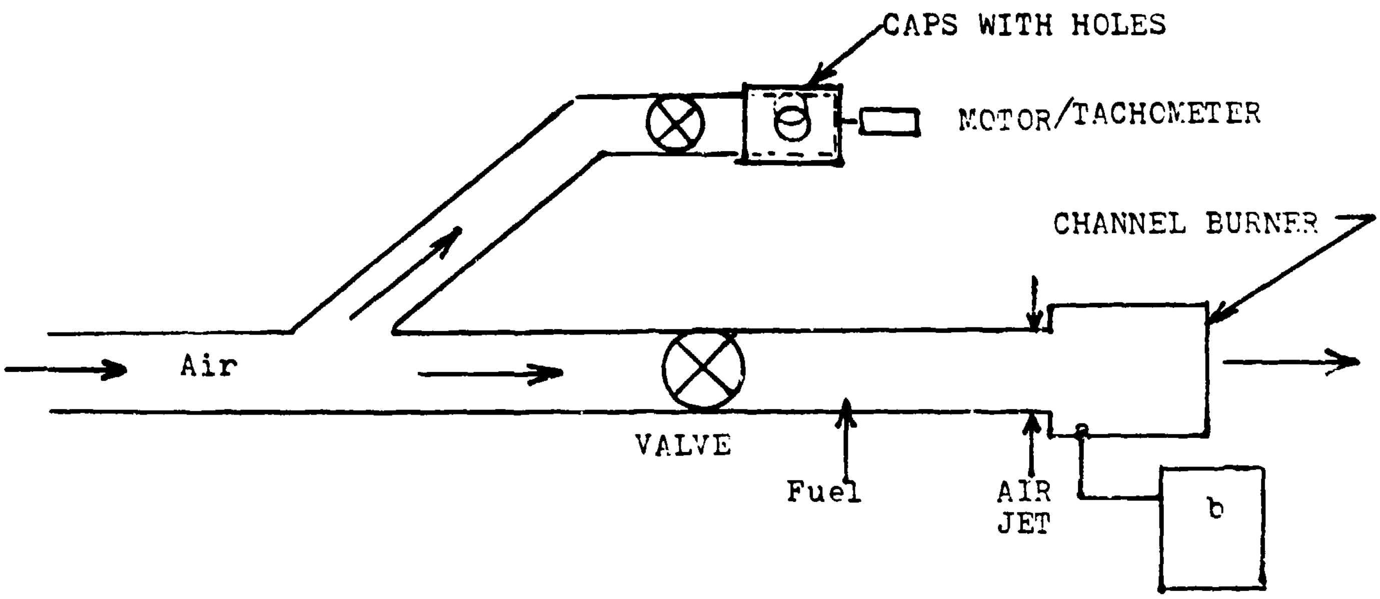
Co-Principal Investigators
Mechanical Engineering Department
University of Southern California
Los Angeles, California 90007

There are several objectives of this program. First, the flow transients in the inlets of dump combustors which are responsible for pressure oscillation and rough burning are being investigated. Special emphasis is placed upon the spectral character and amplitude of the input disturbance which induces combustion instability in a dump combustor. The second objective is to try to identify the chemical nature of the products of liquid phase decomposition during the evaporation of a liquid fuel at an elevated pressure typical of an advanced airbreathing propulsion. The third objective is to conduct selected controlled Fuel-Air Explosion tests to develop criteria for a programmed evaporation to form sensitized fuel-air explosions and to create explosive clouds.

The most important of the mutually interacting multiple vortices in a side dump combustor has been identified. With proper control of the main vortex at the head, it is possible to have a very stable flame holding in a combustor with a low temperature exhaust and consequently low IR and visible signatures. A novel concept of a feed-back loop is presently under investigation which could, in principle, significantly reduce the possibility of combustion instability induced by the pressure fluctuation in the inlet.

Preliminary IR spectrophotometric analyses of fuel droplets whose evaporation has been interrupted show that the products of decomposition are not soluble in the liquid phase. As a matter of fact, the residue particles are insoluble and are suspended in the liquid phase. This result allows a major simplification in the analysis of the coupling between evaporation and decomposiiton by removing the exponential nonlinearity in the decomposition rate equation.

Figure 1 is a sketch of the combustor with induced pressure oscillation. Figure 2a shows the concept of feed-back system in a side dump combustor. The effect of the solubility of decomposition product in the liquid fuel is shown in Fig. 2b.



a: PCB PRESSURE TRANSDUCER
b: HP FREQUENCY ANALYSER

Figure 1. Sketch of flow pulsing device in a channel burner.

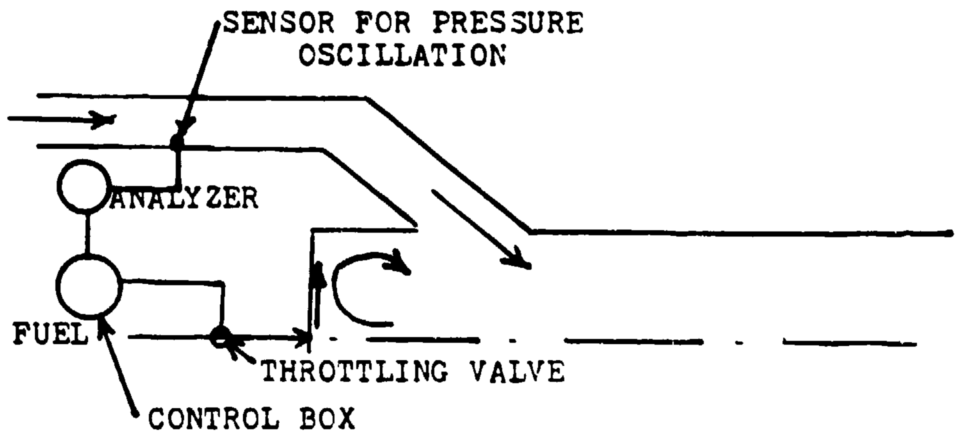


Figure 2a. Sketch of a Feed-Back System for Decreasing Combustion Oscillations in a Side Dump Combustor.

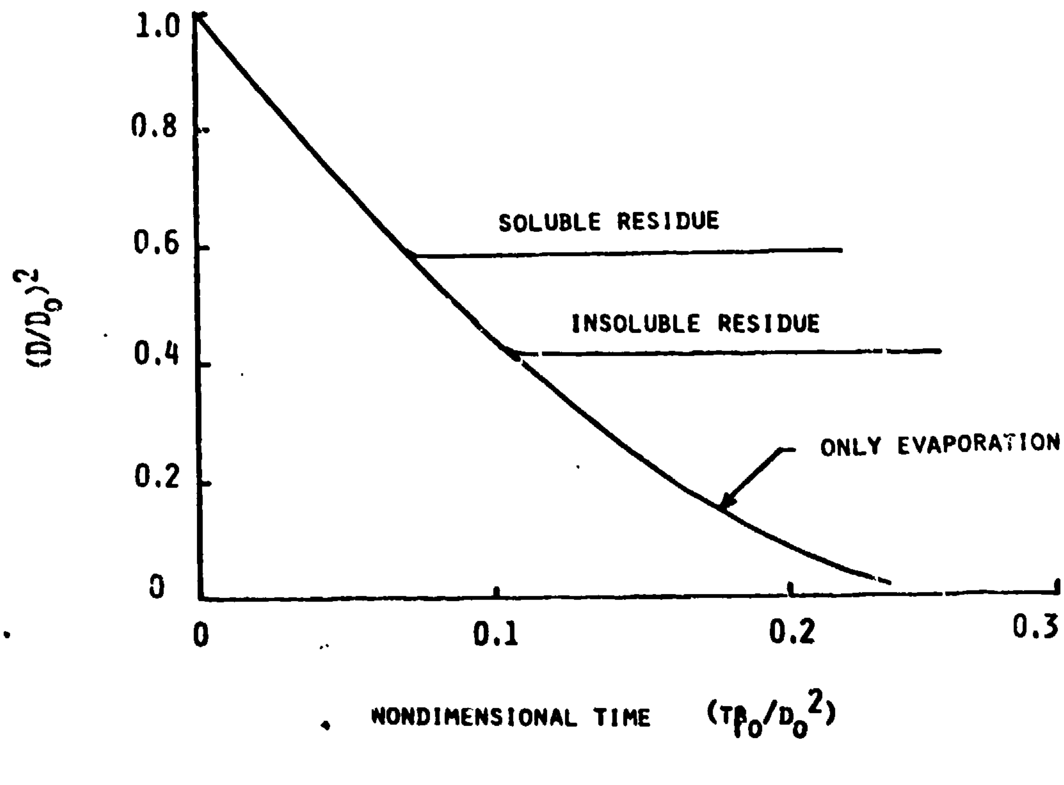


Figure 2b. Effect of Soluble and Insoluble Residue for a 100 micron Hexadecane Fuel Droplet.

Thursday AM Session

8:00 Morning Chairman

D.M. Roquemore
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories

8:05 Research at LLL on Advanced Diagnostic Techniques and Airbreathing Combustion Dynamic Related Phenomena

D.L. Hartley
Sandia National Laboratory

8:30 AFOSR Supported Research and Needs in the Area of Advanced Diagnostics and Instrumentation for Chemically Reacting Flow Systems

L. Caveny
Air Force Office of Scientific Research (AFOSR)

9:00 Studies of Combustion Processes in APL Combustion Research Facility

R.P. Bradley & D.M. Roquemore
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

9:25 Coherent Structures in Turbulent Flames

N. Chigier
Sheffield University/Carnegie-Mellon University

9:50 Measurement of Turbulence in Combustion Systems by Raleigh Scattering

L. Talbot and F. Robbins
University of California - Berkeley

10:15 BREAK

10:30 Laser Velocity Measurements and Analysis of Turbulent Flows with Combustion

W. Stevenson
Purdue University

10:55 Combustion Diagnostics in Practical Combustion Systems Employing the CARS Technique

L. Goss
Systems Research Laboratories

11:20 High Temperature Catalytic Combustion

F. Bracco
Princeton University

11:55 LUNCH

DUMP COMBUSTOR MODELLING AND EXPERIMENT (AFOSR-79-0049)

Ken Bray, Barrie Moss, Ian Shepherd
Department of Aeronautics and Astronautics
The University, Southampton, England.

The present research programme seeks to investigate the detailed mechanisms of turbulent transport and turbulence production in a confined premixed flame. The burner configuration is selected to simulate aspects of dump combustion. Confidence in the physical basis underlying developments in computational models is essential if such models are to prove valuable as aids in combustor designs lying beyond current experience.

A key element in mathematical closures of the averaged equations describing turbulent combustion is the model for turbulent transport. It is customary to model this process by analogy with cold non-reacting flows. Recent work has indicated that this strategy may be quite inappropriate - particularly in weakly-sheared premixed flames - to the extent of predicting the flux to be of the wrong sign. An alternative approach has been suggested which proposes the differential effect of a self-induced mean pressure gradient on the light (burnt) and heavy (unburnt) fluid elements as a dominant transport process. This alternative model requires detailed information on the joint pdf for velocity and scalar progress variables. In the present experiments, laser diagnostics - LDA and light scattering - provide simultaneous measurements of velocity and density with the necessary spatial and temporal resolution.

The burner configuration and data organisation facilities are illustrated in Fig.1. Key features are the use of a tracking filter for laser Doppler signal processing and particulate seeding in the form of TiO_2 smoke produced by the room temperature reaction between titanium tetrachloride and water vapour. This combination permits simultaneous determination of velocity and density using common collection optics and a single photomultiplier tube. Under the assumption that burning takes place locally in thin flame zones, the scalar pdf is restricted to entries corresponding to unburnt mixture and fully burnt gas. Such behaviour, confirmed in the present investigation by light scattering and thermocouple measurements, facilitates data analysis as shown. Conditioned velocity statistics, corresponding to conditions prevailing in unburnt and fully burnt gas, may be readily related to the turbulence properties of interest.

Figure 2 illustrates preliminary data from a streamwise traverse into the burning regime. The results indicate that the conditioned mean velocity in burnt gas exceeds that in unburnt mixture and hence that turbulent transport takes place in the countergradient sense - in contradiction of the eddy transport assumption commonly employed. The streamwise turbulence intensity is also revealed to increase in the burning regime.

FIG.1 APPROACH

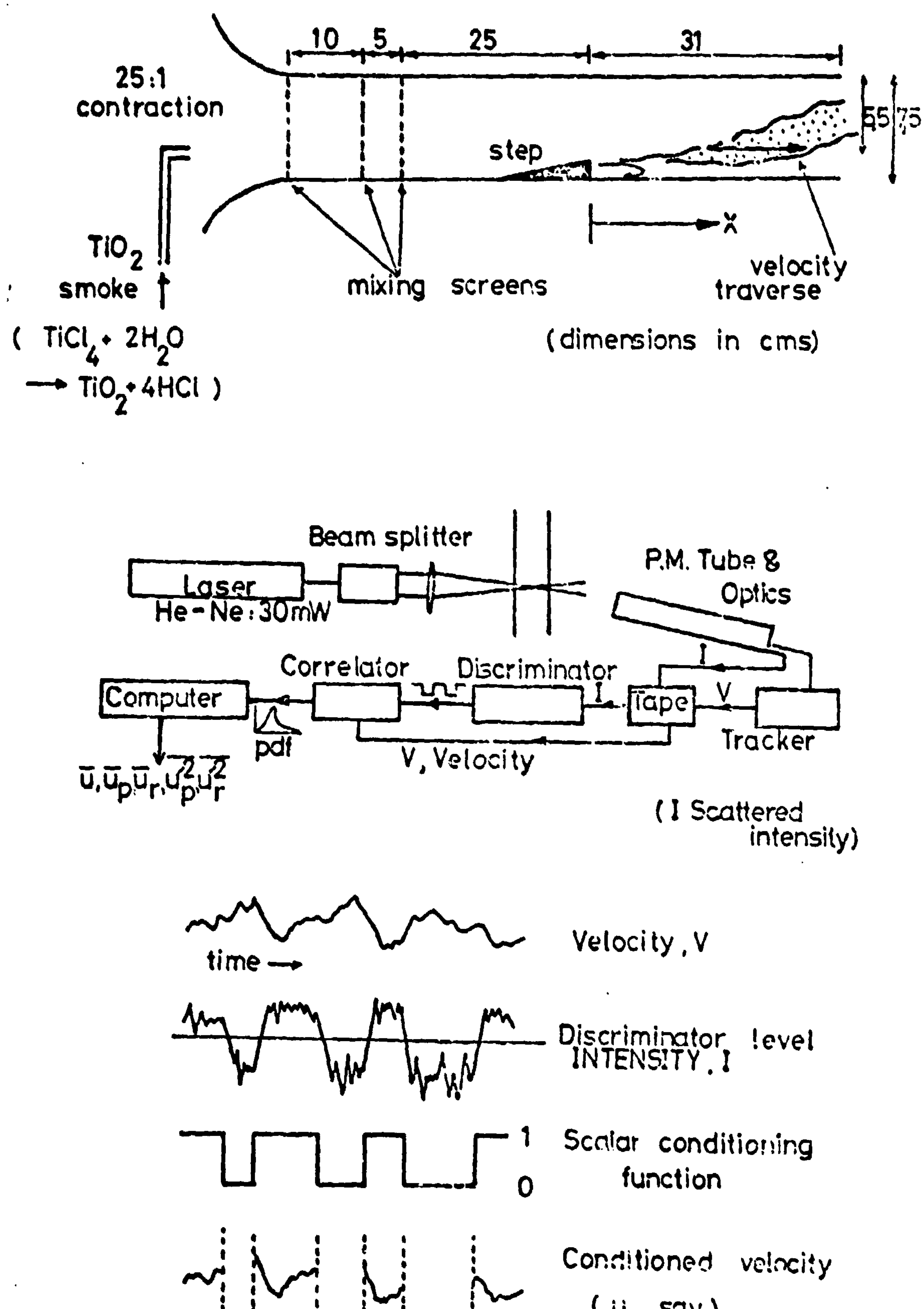
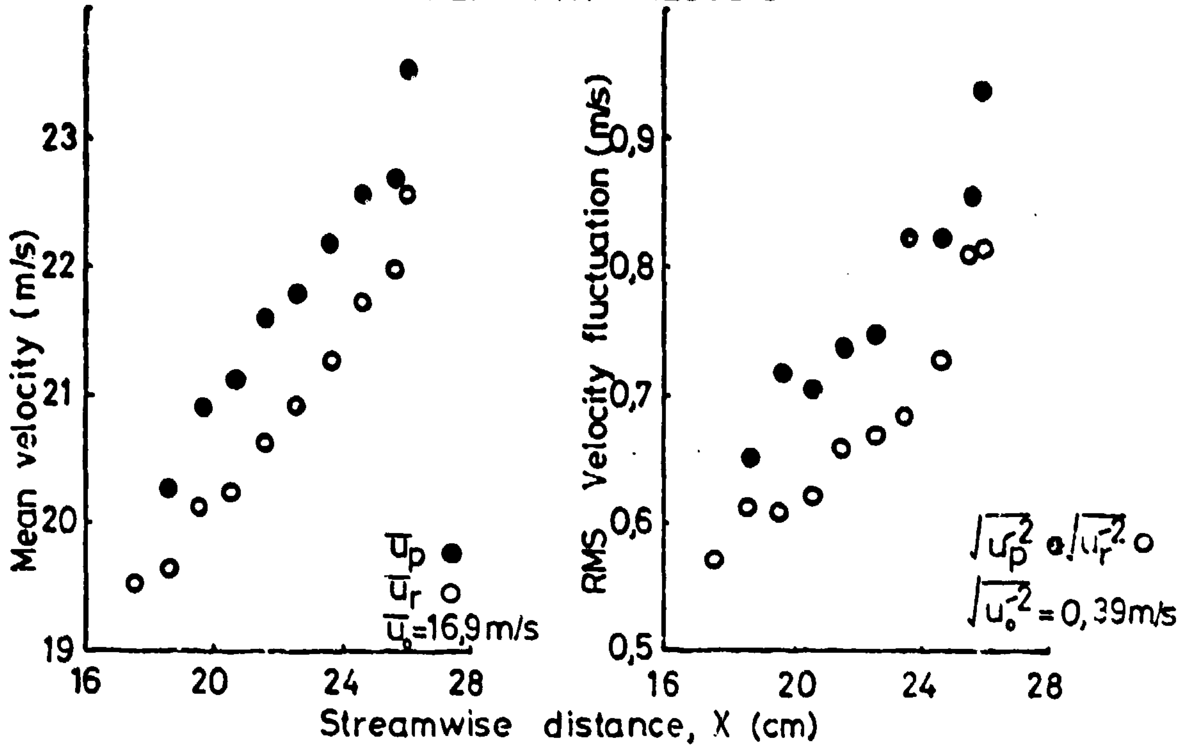


FIG. 2 PRELIMINARY RESULTS

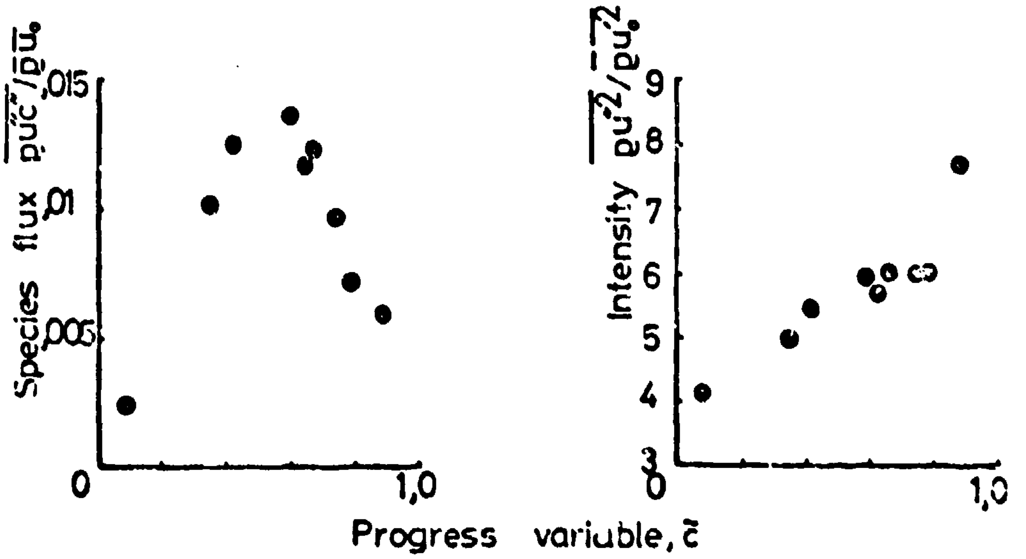


Under the thin flame assumption (burning mode probability $\gamma \ll 1$):

turbulent species flux, $\overline{\rho u''c''} = \bar{\rho}\tilde{c}(1-\tilde{c})(\bar{u}_p-\bar{u}_r)+O(\gamma)$

turbulent intensity, $\overline{\rho u''^2} = \bar{\rho}\left[\tilde{c}(1-\tilde{c})(\bar{u}_p-\bar{u}_r)^2+(1-\tilde{c})u_r'^2+\tilde{c}u_p'^2\right]+O(\gamma)$

where ($\tilde{\ }$), ($\bar{\ }$) denote Favre and Reynolds averages respectively and ( )'' is the Favre fluctuation.



RESEARCH AT SANDIA ADVANCED DIAGNOSTIC TECHNIQUES AND AIRBREATHING COMBUSTION DYNAMIC RELATED PHENOMENA

D.L. Hartley
Sandia National Laboratory
Livermore, Ca

<u>ABSTRACT NOT AVAILABLE</u>

AFOSR SUPPORTED RESEARCH AND NEEDS IN THE AREA OF ADVANCED DIAGNOSTICS AND INSTRUMENTATION FOR CHEMICALLY REACTING FLOW SYSTEMS

L. Caveny

AFOSR/NA
Bolling AFB D.C.

ABSTRACT NOT AVAILABLE

STUDIES OF COMBUSTION PROCESSES

IN THE

APL COMBUSTION RESEARCH FACILITY

ROYCE P. BRADLEY, W. M. ROQUEMORE, J. S. STUTRUD AND C. M. REEVES

AERO PROPULSION LABORATORY, WRIGHT-PATTERSON AIR FORCE BASE, OHIO

A program is in progress at the Aero Propulsion Laboratory (APL) to evaluate combustion models in environments that simulate many of the features of gas turbine combustors. This program involves the selection and evaluation of appropriate diagnostic techniques for making time-averaged and time-resolved point measurements of velocity, temperature and major species concentration profiles in a research combustor at APL. Conventional techniques such as thermocouples and gas sampling probes as well as nonintrusive optical techniques such as laser Doppler anemometry (LDA), coherent anti-Stokes Raman scattering (CARS), and spontaneous Raman scattering are being investigated. Flame radiation measurements and high speed motion pictures are also being used to study the combustion processes.

The program is a composite of several efforts involving both contractor and government participation. The University of Dayton Research Institute is responsible for the LDA, spontaneous Raman, and high speed laser shadowgraph systems and for model evaluations. Systems Research Laboratories is responsible for CARS development and utilization. APL is responsible for program management, facility operation, conventional probe measurements, flame emissions measurements, data analysis and data compilation.

The program has been in progress for about three years. Much of this time has been spent in developing the combustion facility and the laser diagnostic

techniques to be used in the facility. The combustor consists of a 14 cm diameter shrouded disk centrally located in a 25.4 cm diameter duct. Gaseous propane is ejected from a 4.8 mm diameter orifice located in the center of the disk. For cold flow experiments, carbon dioxide is used in place of propane. Turbulent mixing of the fuel, which is ejected from the central jet, and air, which is ejected from the annular jet passage between the duct and the disk, occurs in the recirculation zone established in the near-wake region of the disk. The duct has viewing ports that provide optical access to the combustion process. The combustor is operated at barometric pressure and the ejected fuel and air are at room temperature. The simple axisymmetric geometry of the combustor, with clean inlet conditions and a recirculating flow field, represents a compromise between practical combustors and well controlled laboratory burners.

The combustor has been used in various studies including diagnostic evaluation and collection of data for models. The most notable accomplishments include: the development of a semiquantitative understanding of the time averaged flow field for different operating conditions, the compilation of a data package consisting of inlet radial profiles and centerline profiles of axial velocities for both cold and combusting flows, comparisons of velocity data with FREP and TEACH code predictions, the successful evaluation of a hardened CARS system, and the utilization of 8000 frame/shadowgraphic movies and CH flame emissions to study the dynamic behavior of the combustor. Future efforts will include measurements of carbon dioxide and oxygen concentration profiles for cold flow conditions, the evaluation and utilization of a 2-dimensional LDA system for velocity profile measurements, and the utilization of a hardened BOXCARS system for making simultaneous and instantaneous point measurements of temperature and nitrogen concentrations.

COHERENT STRUCTURES IN TURBULENT FLAMES BY LASER ANEMOMETRY

Norman Chigier
Principal Investigator

Department of Mechanical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213

The principle objective of the present research program is to investigate the mechanisms of entrainment and mixing in turbulent flows with combustion. The role of large eddy structures at turbulent burning interfaces is examined. The engulfment of air into jet flames can result in unmixedness and hence influence the rate of formation and destruction of pollutants in combustion systems.

Figure 1 shows how measurements are made in transitional and turbulent flames. Measurements of velocity, temperature and ionization are made as a function of space and time using laser anemometers, fine wire compensated thermocouples and ionization probes. Recording of this data using microprocessors allows conditional sampling to be made. Correlations are also found between ionization probes at different separation distances and using arrays of fine wire thermocouples. The ultimate objective is to relate the time histories of velocity, temperature and ionization with eddy structures determined by high speed movies. Measurements have been made in a range of positions and flames with systematic variation of initial conditions. Mean quantitites and the statistics of fluctuating quantities in the same flames have been mapped. Digitally stored time histories have been processed in several ways and various conditional sampling criteria have been applied to select different features of the flows for investigation.

Studies of vaporizing liquid sprays have continued. A laser tomographic method was developed for determining spatial distributions of droplet size variation using the Malvern laser diffraction meter. Droplet size variations have been determined in sprays vaporizing in heated air streams. Multi-angular scanning is being developed to allow increased precision for tomographic studies. Figure 2 shows measurements by laser anemometer of droplet and gas velocities in liquid sprays. Large differences between droplet and gas velocity are found in the early regions of the spray.

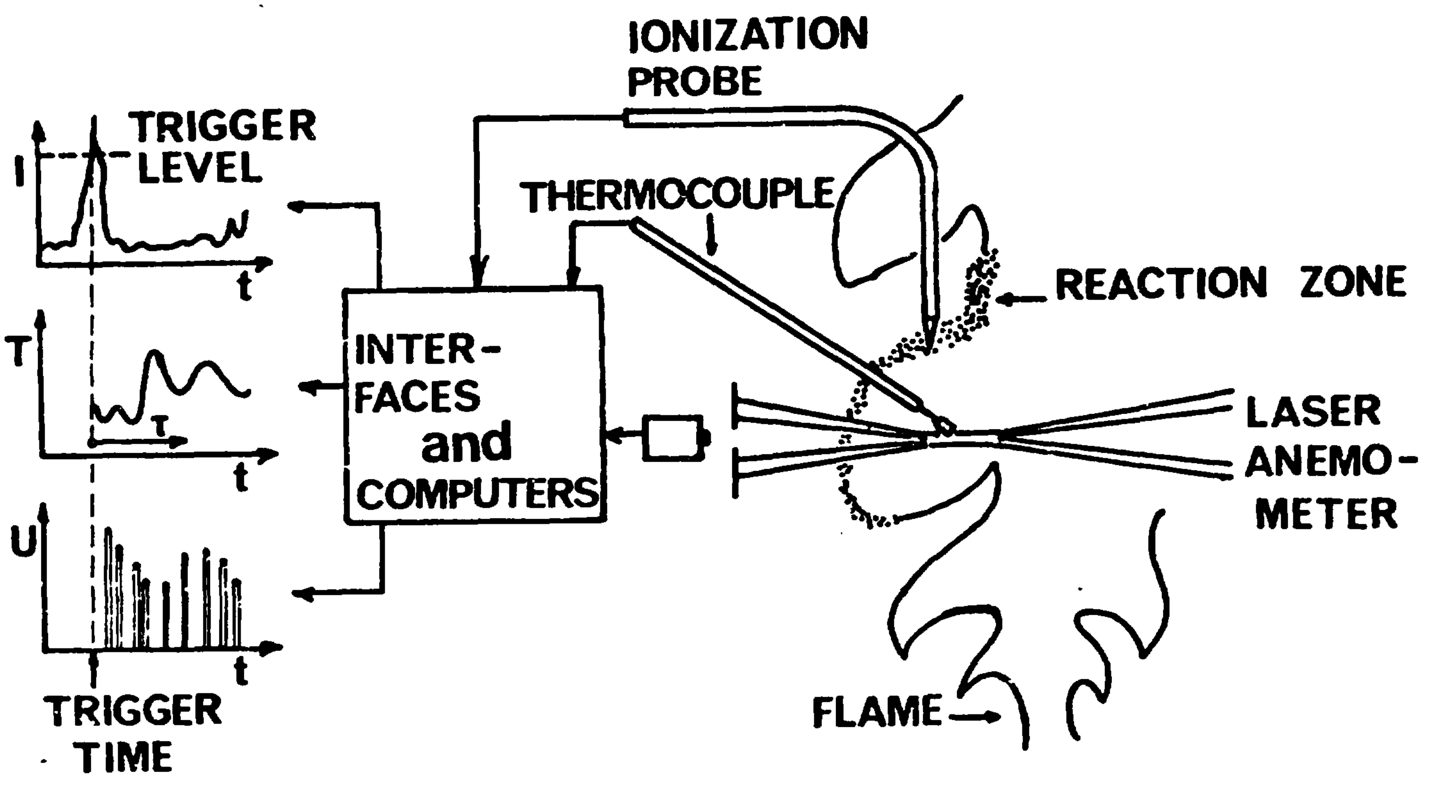


Fig. 1 Conditional Sampling to Measure Local Average Eddy and Reaction Zone Structure

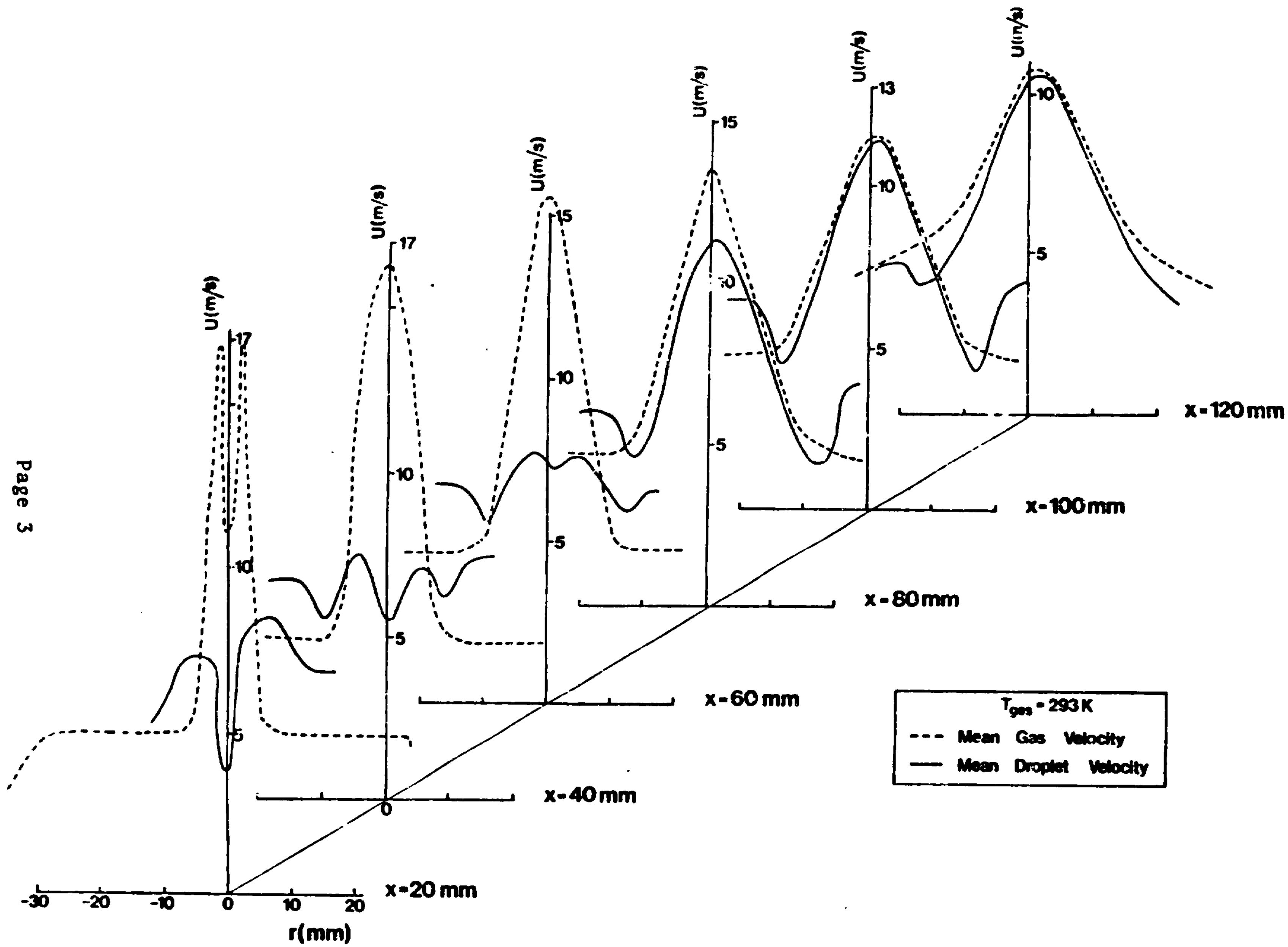


Fig. 2 Separate Measurement of Droplet and Gas Velocity in Spray by Laser Anemometry

Applications of Rayleigh Scattering to Turbulent Flows with Heat Transfer and Combustion

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The technical objective of this research is to investigate the fluid-dynamical aspects of the interaction of turbulent flow with a flame, a reaction front. One important overall objective is to contribute to an experimental data base which will result in an improved understanding of turbulent combustion processes and more accurate numerical modeling in systems of technical interest.

A premixed, V-shaped ethylene/air flame stabilized on a rod transverse to the flow has been studied using Rayleigh scattering to measure the density and laser Doppler to measure the velocity, as shown in Fig. 1. Results have been obtained and published for flame interaction with grid induced turbulence and with discrete Karman vortex street vortices.

The most recent results, the first of their kind, consist of spatial correlation measurements of the density obtained by simultaneous measurement of the Rayleigh scattering at two points. Figure 2 shows preliminary results of the density correlation coefficient versus the distance between the two sampled points in three directions. The correlation across the flame and in the plane of the flame both approach zero at about 5 mm and give an integral length scale of about 2 mm. The correlation in the axial, or flow, direction behaves differently and does not go to zero even at 12 mm, the edge of the flame. Future measurements will be made in the plane of the flame as shown in Fig. 2c.

These results indicate a quite different form of spatial correlation in the downstream direction of the flame which may lead to further understanding of the propagation of disturbances in a turbulent flame sheet. If the present case can be approximated as a thin, wrinkled, laminar flame, as indicated by other measurements as well as dimensional arguments, then some aspects of the statistical form and motion of the wrinkled surface can be obtained.

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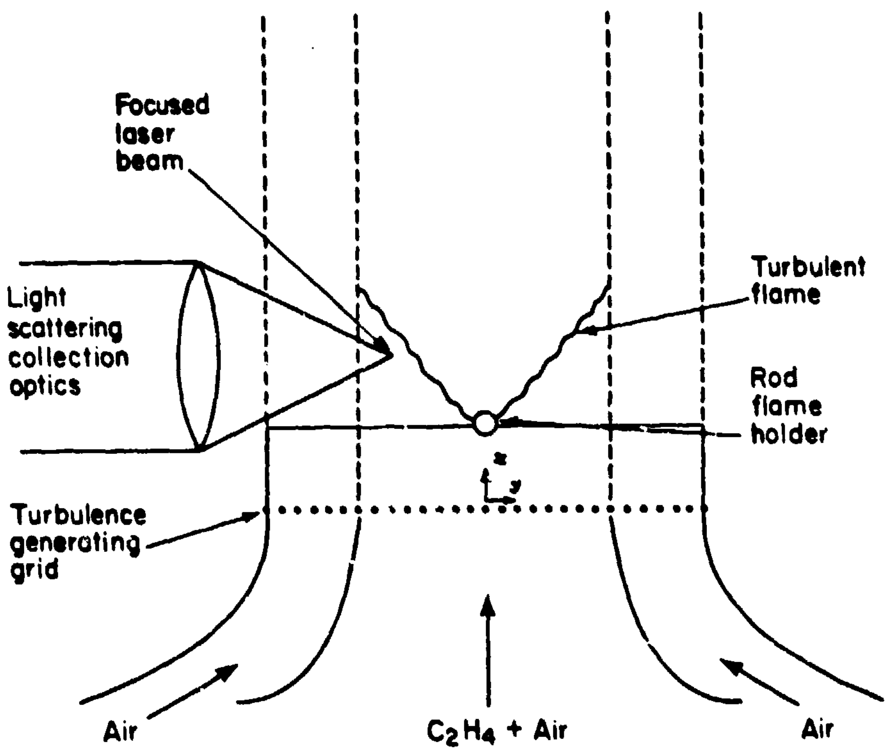

Figure 1. Schematic of the experimental apparatus for studying the propagation of a V-shaped flame in grid-induced turbulent flow using Rayleigh scattering and laser Doppler velocimetry.

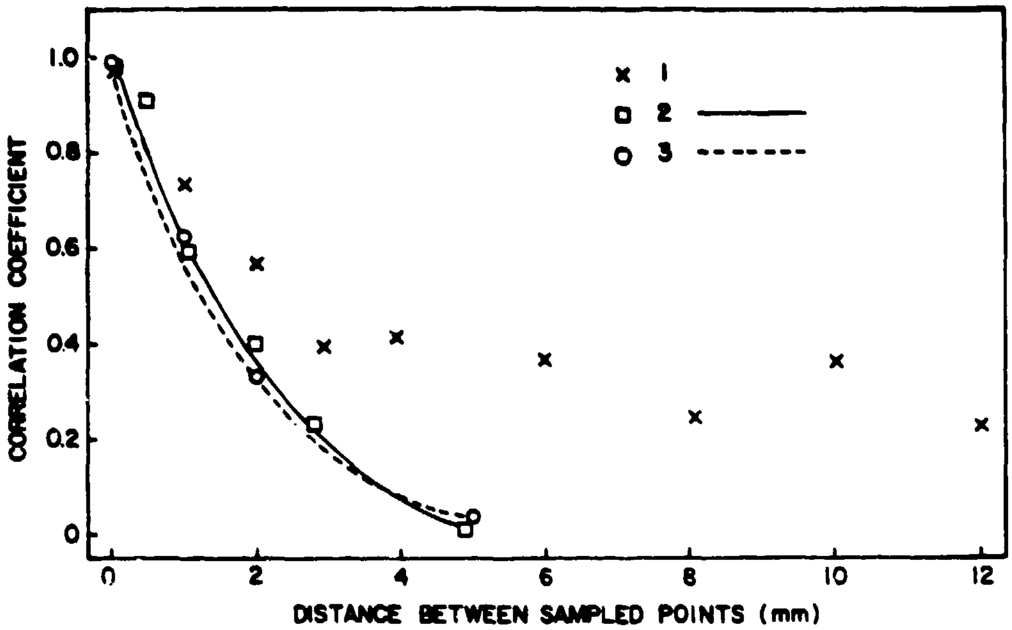

Fig. 2a

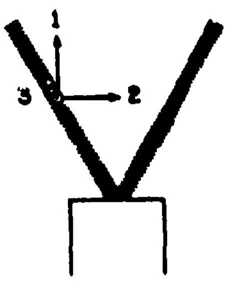

Fig. 2b

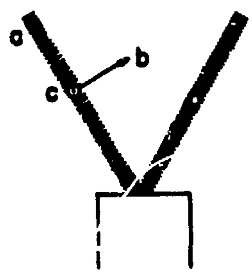

Fig. 2c

-e 2. The density correlation coefficient in a turbulent flame as a function of the distance between the two sampled points in directions 1, 2, and 3 as shown in Fig. 2b. Future measurements to be made as in Fig. 2c. Experimental conditions: ethylene-air at equivalence ratio 0.6; U = 7 m/s; flame half-angle = 12°; measurement point 35 mm downstream from the flame holder.

LASER VELOCIMETER MEASUREMENTS AND ANALYSIS IN TURBULENT FLOWS WITH COMBUSTION

AFAPL Contract No. F33615-81-K-2003

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The overall objective of this research, initiated January 1981, is to investigate "ramjet-like" flows using the laser Doppler velocimeter (LDV). This involves a detailed study of problems encountered in obtaining accurate LDV measurements in turbulent shear flows with and without combustion. Some specific areas to be addressed are the so-called bias error effects, correction for abberations in cylindrical test sections, and the solution of problems associated with making LDV measurements in combusting flows.

Initial efforts have included extensive cold flow measurements in a 3.75 inch D. cylindrical tube downstream of a converging nozzle with an exit diameter of 2 inches. Nozzle exit velocity is approximately 25 meters/sec. Measured and derived quantities are mean axial velocity, turbulence intensity, turbulence kinetic energy, and Reynolds stress. These measurements were made from the inlet nozzle exit plane to a point well beyond reattachment. Bias error was minimized using a data acquisition scheme developed in a previous study. The integrated mass flux obtained from the measured velocity profiles is found to be identical within one percent at all measurement planes, indicating that the LDV results are quite accurate. A modified version of the 2/E/FIX computer code is being used to provide numerical results for comparison to the measured data.

An optical correction element has been designed so that radial velocity component measurements can be made over a sizeable fraction of the tube radius. Such measurements are planned in the near future. A steady flow combustion tunnel has also been designed and fabricated to permit LDV measurements to be made in a geometry similar to the cold flow rig. This system will employ a lean premixture of propane and air to keep operating temperatures at a level where steady flow can be maintained. Initial tests of the combustion system are planned for early 1982.

COMBUSTION DIAGNOSTICS IN PRACTICAL COMBUSTION SYSTEMS EMPLOYING THE CARS TECHNIQUE

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A program is currently underway at the AFWAL Aero Propulsion Laboratory (APL) to develop CARS as a practical combustion-diagnostic tool. This program involves both fundamental studies of small-scale turbulent diffusion flames in the laboratory and detailed studies of a bluff-body combustor located at the APL Combustion Research Facility by a specially constructed environmentally hardened CARS system. A 10-Hz laboratory CARS system capable of simultaneous concentraion and temperature measurements of a major species has been built and used to study a small-scale turbulent burner. The burner consists of a series of concentric fuel and air tubes. Simultaneous temperature and species-concentration probability density functions (PDF) have been obtained in this flame at various locations. The results of these PDF's, high-speed photography, and high-speed schlieren indicate that the turbulence levels are quite high and that a high degree of intermittency exists in this flame. Comparisons with adiabatic flame calculations show good agreement with the concentration and temperature data. The environmentally hardened CARS system is still under construction. The basic design of the system will be discussed, with special attention being given to the hardened features.

HIGH TEMPERATURE CATALYTIC COMBUSTION

F. Bracco
Princeton University
(AFOSR-76-3052)

ABSTRACT NOT AVAILABLE

Thursday PM Session

1:15 Afternoon Chairman

B. Levine
National Bureau of Standards, Gaithersburg, MD

1:20 Radiation Enhanced Ignition, Combustion and Flame Stabilization

M. Lavid
Exxon Research and Engineering Company

1:45 Interfacial Chemical Reactions in Flow Systems

D.F. Rosner
Yale University

2:10 NBS In-House and Supported Research, Development Trends and Research Needs in Airbreathing Combustion, Kinetics, Explosion and Fire Protection

R. Levine
National Bureau of Standards, Gaithersburg, MD

2:35 APL Supported Research, Development Trends and Needs in Aircraft Fire and Explosion Technology

J. Manheim
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

3:00 BREAK

3:15 Ignition of Fuel Sprays by Hot Surfaces and Stabilization of External and Void Space Aircraft Fires

A.H. Lefebvre, J.G. Skifstad & S.N.B. Murthy
Purdue University

3:40 Ignition of Fuels by Incendiary Metal Particles

W.A. Sirignano
Carnegie-Mellon University

4:05 Executive Session
(AFOSR Contractors/Grantees ONLY)

5:00 ADJOURN

RADIATION/CATALYTIC AUGMENTED COMBUSTION

AFOSR Contract No. F49620-77-C-0085

Moshe Lavid
Principal Investigator

Exxon Research and Engineering Company
Corporate Research-Technology Feasibility Center
Linden, New Jersey 07036

The objective of this research is to investigate the feasibility of radiation and catalytic augmented combustion techniques for extending current aircraft operational limitations due to combustion associated phenomena.

The radiation technique utilizes selected wavelengths in the vacuum ultraviolet region (VUV) to photodissociate molecular oxygen into oxygen atoms. When a critical concentration of atomic oxygen is achieved (about 10^{16} atoms/cm^3), combustion initiation occurs. Subsequent reactions of the atomic oxygen with fuel molecules, as well as with other combustion species, lead to ignition and sustained combustion via chain reactions.

Successful experimental results demonstrated the potential opportunity of using radiative augmented combustion as a technique to extend current combustors operating limits. Various gaseous mixtures have been ignited over a wide range of equivalence ratios by using appropriate light sources. In two cases the photochemical ignition caused a transition into a detonation wave which shattered the quartz reactor. Combustion enhancement in terms of flame propagation were measured, showing an increase of about 20%.

The recent primary accomplishment of this work was the investigation of the effect of light wavelength on combustion augmentation. By employing an Excimer laser at two VUV wavelengths 157 nm (F_2) and 193 nm (ArF), we found that the shorter wavelength laser (F_2) is very capable of achieving radiative ignitions and that it is by far the best available VUV source for the radiative technique. These recent findings are in full agreement with our analytical predictions. The upper half of Fig. 1 shows that when the radiative energy is uniformly distributed over a broad band of wavelengths, 140 to 360 nm, the minimum relative energy required for ignition is 5.8 units. The lower half of Fig. 1 demonstrates that by selecting a narrow band near the F_2 laser, 145 nm to 155 nm, the ignition energy is reduced to 0.3. This is a significant reduction of about 20 fold! This prediction was corroborated with laboratory measurements. We measured a net VUV fluence of 20 and 350 mJ/cm^2 for the F_2 and ArF lasers, respectively. Although the fluence of the F_2 laser is considerably smaller than that of the ArF laser, it successfully achieved ignition, while the ArF was unsuccessful in igniting the same gaseous mixtures.

The catalytic combustion is a concept wherein combustion reactions initiated by a heterogeneous catalyst play an important role in the energy release process of a reacting fuel-air system. This research proposed to replace the conventional bluff-body depicted in Fig. 2(a), by catalytic flameholder described in Figs. 2(b) and 2(c). The bluff-body stabilizes the combustion by forming a recirculation zone which, in turn, enhances mixing and heat transfer. However, it also causes a substantial pressure loss. The catalytic flameholder, depending on its porosity, may or may not have a recirculation zone. The key role of the catalyst is to "bootstrap" the conditions of temperature and concentration of reactive species to levels favorable for stable and efficient combustion. The advantages of the catalytic flameholder over the bluff-body are: (1) reducing the pressure loss and (2) providing more stable combustion due to its porous structure and its thermal inertia, respectively.

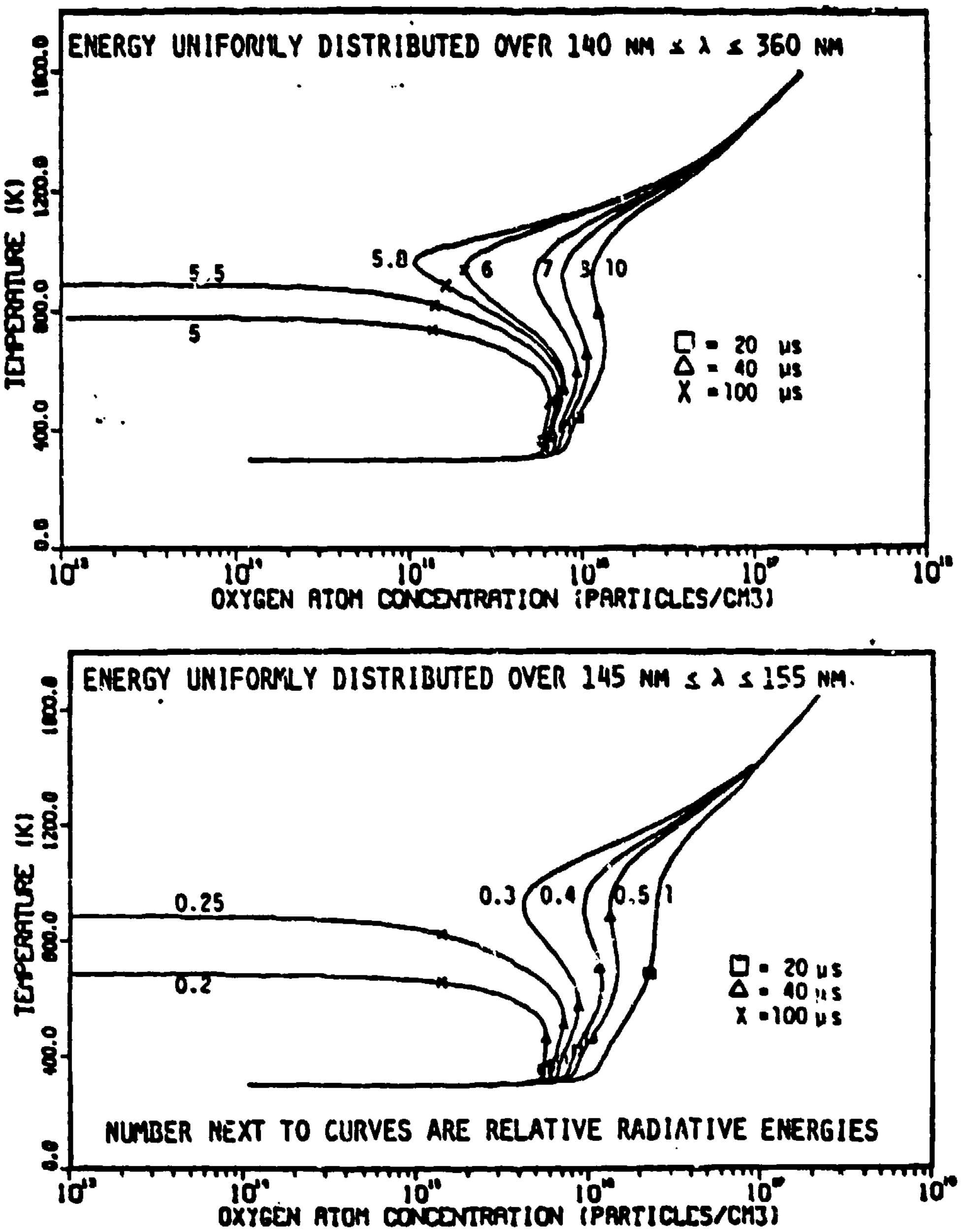
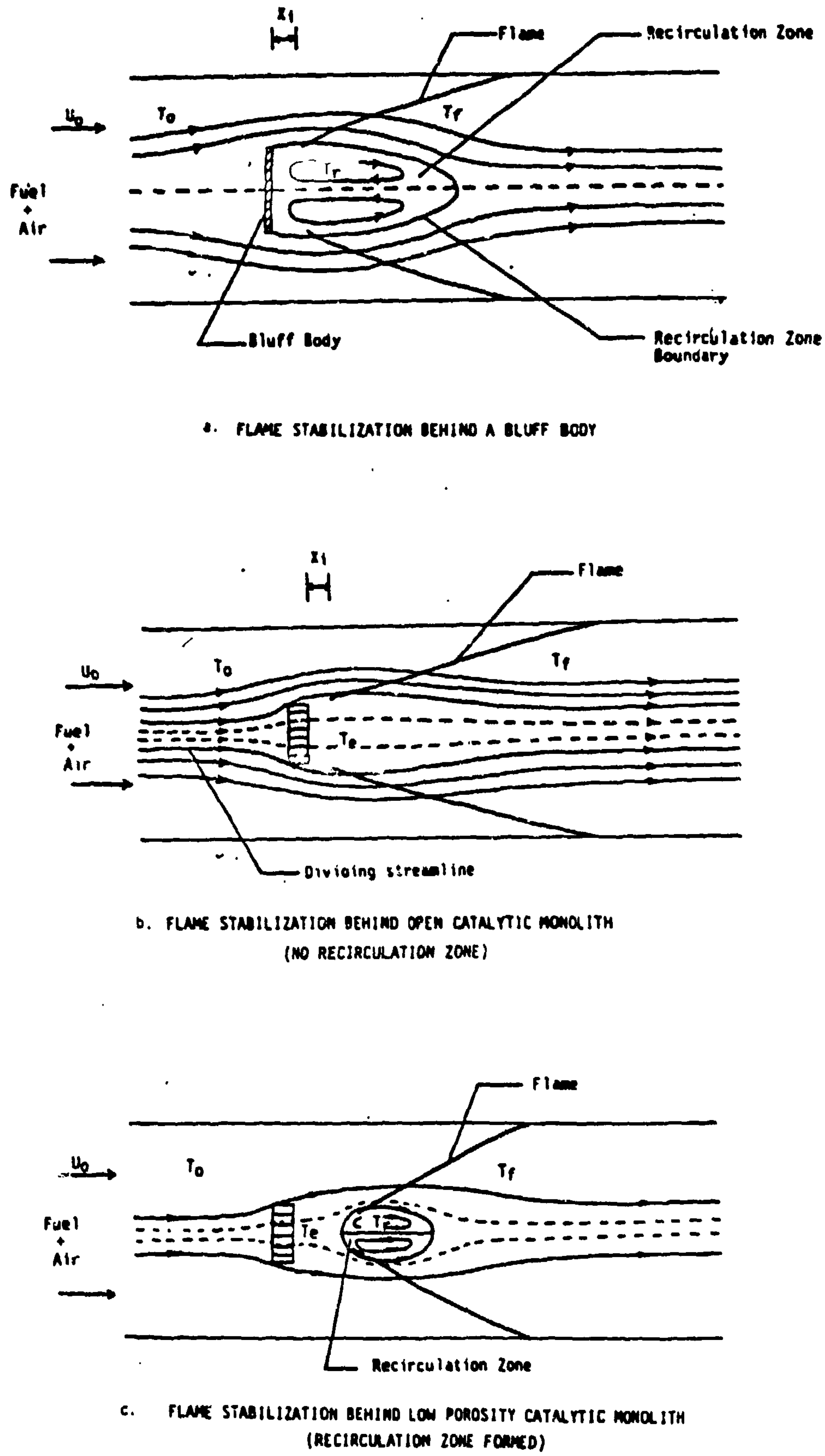


FIGURE 1. PHASE PLANE PATHS RESULTING FROM ADIABATIC PULSED VACUUM ULTRAVIOLET IRRADIATION OF STOICHIOMETRIC HYDROGEN/OXYGEN MIXTURE



a. FLAME STABILIZATION BEHIND A BLUFF BODY

b. FLAME STABILIZATION BEHIND OPEN CATALYTIC MONOLITH
(NO RECIRCULATION ZONE)

c. FLAME STABILIZATION BEHIND LOW POROSITY CATALYTIC MONOLITH
(RECIRCULATION ZONE FORMED)

FIGURE 2. BLUFF-BODY AND CATALYTIC FLAMEHOLDERS

INTERFACIAL CHEMICAL REACTIONS AND TRANSPORT PHENOMENA IN FLOW SYSTEMS

(Contract F49620-76C -0020)

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Principal Investigator
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Yale University, New Haven, CT 06520

The performance of high energy combustion systems cannot be understood, predicted, or optimized without a sufficiently complete knowledge of the laws of convective-diffusion mass and heat transport, since these physical phenomena usually limit, if not completely control, combustion rates. We are presently investigating the important but hitherto neglected role of thermal diffusion [1] (Soret effect for vapors, thermophoresis for particles) in determining the rates at which: light or heavy fuel vapors diffuse to the active surface in catalytic combustion (Fig. 1a); particulate soot and/or condensed products of a vapor phase diffusion flame are transported to/from the reaction zone (Fig. 1b) or captured in sampling devices; and salts, fuel ash or soot deposit on gas turbine blades (Fig. 1c).

Our approach is to combine experimental laser reflectivity-based measurements using a unique, seeded flat-flame combustor[2] (Fig. 1d), with boundary layer theory[1,3] to develop practical methods for incorporating the dominant effects of thermophoretic transport in combustion systems.

Optically determined deposition rates of $K_2SO_4(s)$, obtained using a propane/air flame seeded with a K_2SO_4 aqueous solution aerosol, are shown as a function of target temperature in Fig. 2. These data exhibit the existence of a "dew point" temperature, expected in vapor transport systems. This work is currently being extended to include optical measurements of aerosol (TiO_2, MgO, CaO,...) transport from high temperature combustion products.

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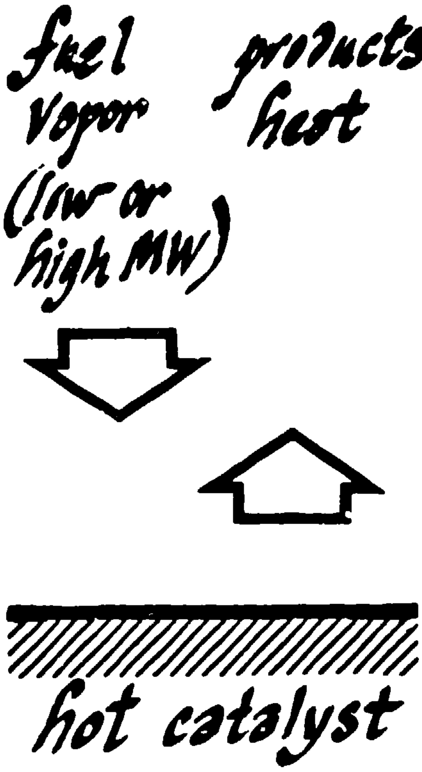
[1] Rosner, D. E., "Thermal (Soret) Diffusion Effects on Interfacial Mass Transport Rates", Physico-Chemical Hydrodynamics, 1, 159-185 (1980)

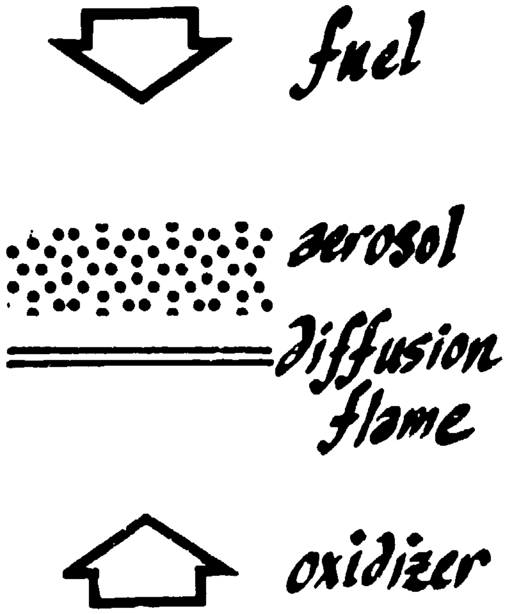
[2] Rosner, D. E. and Seshadi, K., "Experimental and Theoretical Studies of the Laws Governing Condensate Deposition From Combustion Gases", 18th Combustion Symposium, The Combustion Inst. (1981), pp. 1385-1394

[3] Rosner, D. E. and Fernandez de la Mora, J., "Correlation and Prediction of Thermophoretic and Inertial Effects on Particle Transport Across Non-Isothermal Turbulent Boundary Layers", to be presented at the 27th (ASME - IME) International Gas Turbine Conference (London, April, 1982)



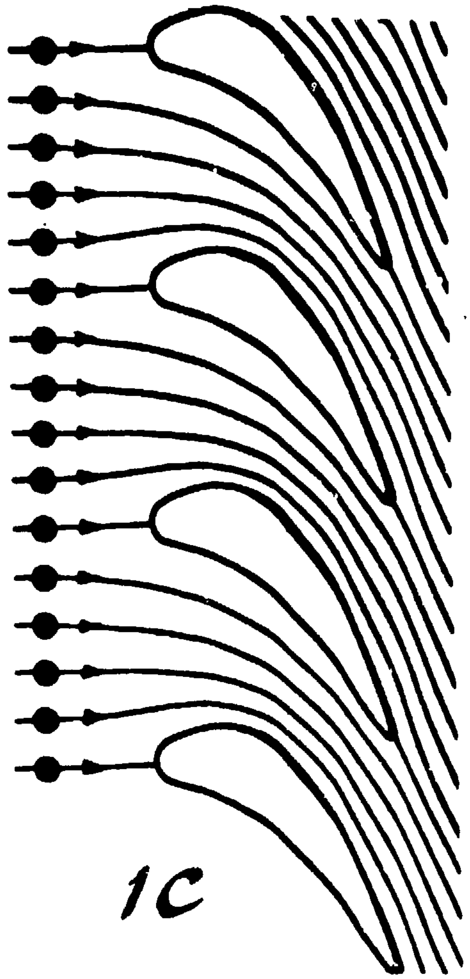
fuel vapor (low or high MW)
products, heat
hot catalyst

1a

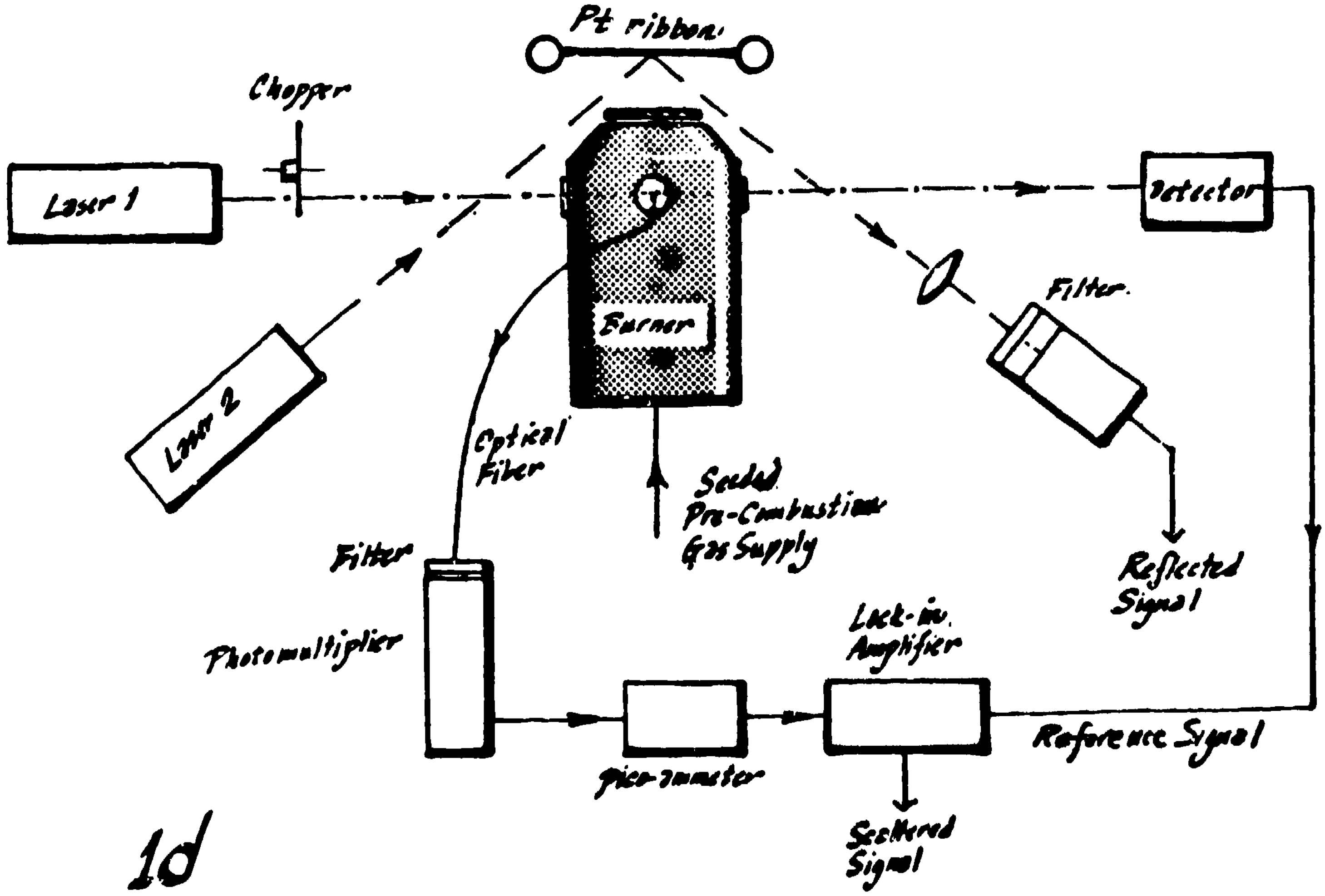


fuel
aerosol
diffusion flame
oxidizer

1b



1c



Pt ribbon
Chopper
Laser 1
Laser 2
Detector
Burner
Filter
Optical Fiber
Seeded Pre-Combustion Gas Supply
Filter
Photomultiplier
Reflected Signal
Lock-in Amplifier
Reference Signal
pico-ammeter
Scattered Signal

1d

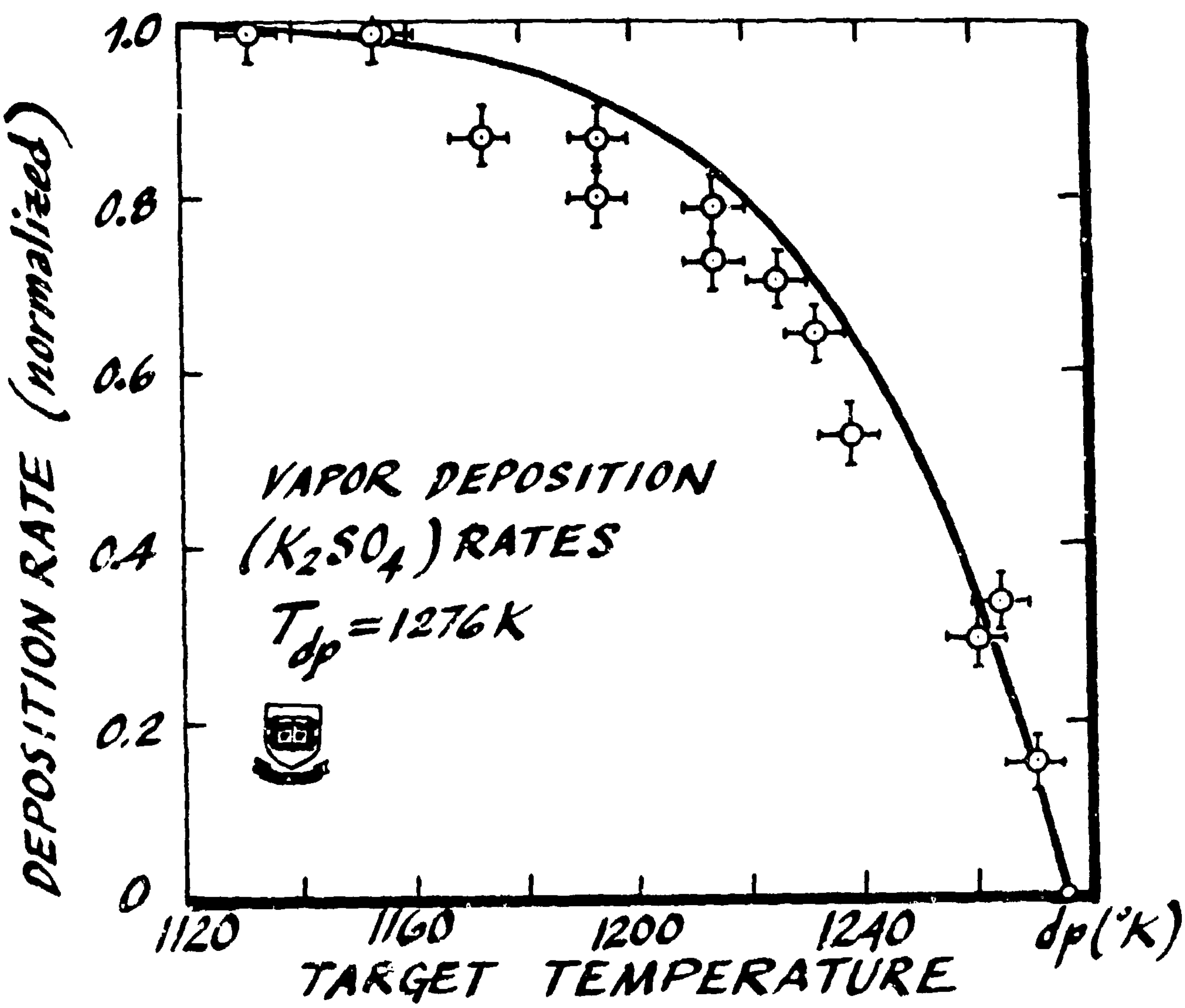


FIG. 2 : Normalized K_2SO_4 deposition rate from seeded propane/air flame as a function of target temperature; data points inferred from experimental re-sublimation times

NBS IN-HOUSE AND SUPPORTED RESEARCH APPLICABLE TO AIRBREATHING COMBUSTION KINETICS, EXPLOSIONS, AND FIRE PROTECTION

Robert S. Levine

Abstract

Analysis and correlation of kinetic data for elementary reactions is continuing for general use. The kinetic data are being utilized in NBS along with standard thermo-analytical techniques to predict the occurrence of pollutants such as dioxins, carbon, and tars from burning complex refuse-derived fuels. It is hoped that by determining the most difficult to destroy undesirable species, EPA or DOE can set incineration criteria for mixed wastes.

Diagnosis and analysis of gaseous turbulent diffusion flames is being carried out both on low initial momentum flames characteristic of unwanted fire, and on jets characteristic of furnace burners. One feature of the latter is the use of optical tomography to give two-dimensional profiles of concentrations and temperature at a given axial position in the jet. Combinations of modern optical analysis techniques such as laser Raman are routinely used in these projects. Buoyant plume growth is analyzed mathematically using "field equations" in a two-dimensional program. Computer resources that will permit calculations of plume growth in three-dimensions will be provided in the future.

Air Force support contributes to the analysis of the ignition process of pyrolyzed fuel above an irradiated solid. Two-color laser holography is utilized to derive simultaneous temperature field and composition field measurements in the gas phase. Ignition takes place in the gas phase at temperatures above the pyrolysis temperature of the solid. This temperature rise in the gas phase is possibly caused by a combination of absorption of the IR radiation and pre-ignition reactions.

The processes leading to the formation of particulates are being investigated in laminar diffusion flames both in-house and under grants. Laser pulses thermally ionize the particulates, and the ions and electrons diffuse to an electrode at a speed depending on their charge and mass. Ionic processes are possibly involved in the very early stages of particulate formation, and other ionic processes are involved in later stages of particle growth. Laser scattering/extinction techniques are also being used to investigate soot formation and oxidation processes.

The basic chemical processes of solid phase pyrolysis are being studied in both cellulosic and synthetic polymers. It is hoped this research will give insight into the understanding and control of smoldering combustion, and into improved ways of incorporating fire retardancy into solid materials.

Applied combustion-related research tasks are heavily oriented to the generation and utilization of computer models of fire growth in enclosures such as rooms or airplanes. Improved information is being sought on fire spread and burning rate as affected by radiant heat transfer, air heating and vitiation, etc. This new information is then cast in the form of computer algorithms to improve the models. In close cooperation with the Federal Aviation Administration, these modeling techniques are being tested against their experimental data to describe fire hazard growth and passenger tenability in a crashed airplane in, for instance, a pool fire of jet fuel. Another facet of this effort is the evaluation of standard fire test methods for materials as related to aircraft fire safety.

Other combustion-related projects include investigation of combustion processes for refuse derived fuels and for coal-derived fuels, spectroscopic techniques for combustion control in furnaces, development of instrumentation for time-resolved diagnostics inside solid-fuel reactors, fire and health safety of a new generation of unvented gas-fueled heaters, and specialized instruments.

University research, by grant or by informal agreement, supports many of these programs. In each case, the university research is monitored by a NBS "scientific officer" who is involved in related research.

APL SUPPORTED RESEARCH, DEVELOPMENT TRENDS AND NEEDS IN AIRCRAFT FIRE AND EXPLOSION TECHNOLOGY

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<u>ABSTRACT NOT AVAILABLE</u>

IGNITION OF FUEL SPRAYS BY HOT SURFACES

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The experimental portion of this investigation is designed to obtain basic data for relatively simple boundary layer flows, such as that illustrated in Fig. 1a, in which most of the pertinent variables of the problem can be independently controlled. Properties of the flowfield, such as the Reynolds number of the boundary layer, the temperature and pressure of the gas flow, the fuel/air ratio, the spray properties (SMD, fraction of fuel vaporized) and others, such as the wall conditions, are to be varied independently for a variety of liquid (or gaseous) fuels, for example. Measurements of local properties in the boundary layer both upstream and downstream of the heated surface will provide a basis for evaluation of theoretical models of the phenomena, incorporating two-phase transport, wall phenomena and chemistry leading to ignition.

A facility has been developed and tested for these investigations in which the relevant parameters of the problem may be varied independently. This facility, shown in Fig. 1b, comprises a special flow preparation system in which the liquid fuel is sprayed by an array of small airblast injectors into a preconditioned gas flow, which then passes over a surface heated electrically. Local flowfield measurements are made both upstream and downstream of the heated surface by optical methods and by means of a sampling probe system, along with measurements of other data such as the wall temperatures, pressures, flow rates and various manifold conditions. Procedures for laser velocimeter measurements in the fuel sprays of interest have been developed and tested. A heated sampling probe with a special catalytic combustor and a gas analysis system has been developed for measurements requiring the sampling technique. A special imaging-type spray analysis system has been developed for use on this and other research programs in our laboratory for the purpose of making local measurements of the droplet number density and size distribution function.

Local spray measurements in the boundary layer, such as those represented in Fig. 2a, together with other local measurements in the boundary layer, will yield information to evaluate the merit of various theoretical models for the development of the thermal boundary layer and the physico-chemical phenomena leading to ignition. The investigation is to yield two types of information: a) correlations for ignition conditions in terms of the relevant parameters of the study for various liquid and gaseous fuels, and b) evaluation of boundary layer models of the flowfield, which would be useful both for the prediction of flow conditions leading to ignition in most practical situations of interest and for development of measures to prevent aircraft fires initiated by the mechanisms established in the investigation.

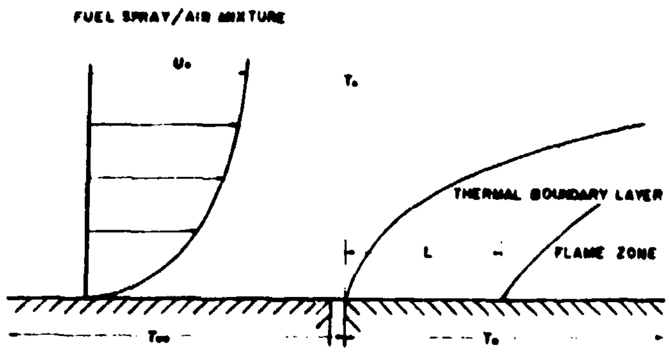

Figure 1a. Flowfield for Hot Surface Ignition of Fuel Sprays

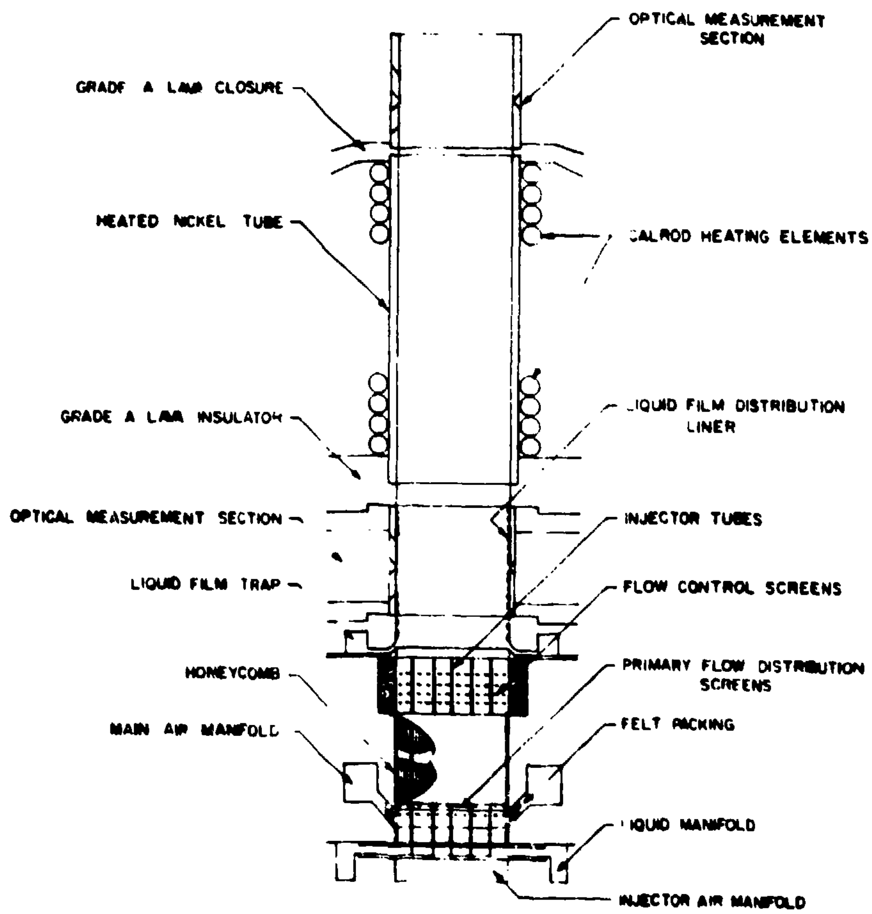

Figure 1b. Experimental Apparatus for Spray Ignition Research

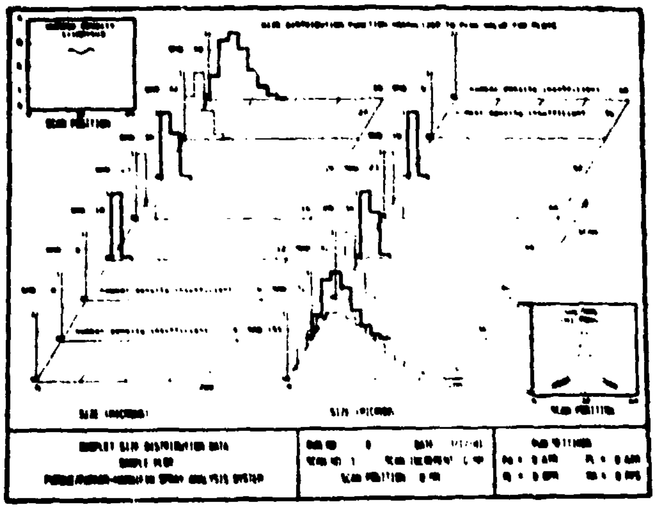

Figure 2a. Representative Spray Measurements

ANTICIPATED RESULTS

A) Correlations of ignition limits with Re, f/a, fraction of fuel vaporized, droplet size, air temperature, pressure and wall conditions for various liquid and gaseous fuels.

B) Evaluation of boundary layer models for representation of the development of the thermal boundary layer in the two-phase flows of interest under conditions leading to ignition.

Stabilization of Fires by Large-Scale Flameholders

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Principal Investigator

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One objective of the research is to extend the range of experimental data on the stabilization properties of bluff-body flameholders to include flameholders of large size (characteristic dimension up to 10 cm) and irregular shape, such as might arise on the external surface of an aircraft due to structural damage. Another goal is to derive suitable theoretical relationships to describe stabilization performance for the extended range of flameholder sizes and shapes.

Stability loops are obtained by the water injection technique, as shown schematically in Fig. 1. The flameholder under test is placed near the exit of a duct supplied with an airflow containing a water/fuel mixture. Both the water and fuel (Jet-A) are fully vaporized by the time they reach the flameholder. At the start of a run the fuel/air ratio is set and the flame is established with no water injection. The water flow is then initiated and increased until flame extinction occurs. A plot of the stability loop so obtained (equivalence ratio versus water/fuel ratio) is equivalent to a plot of equivalence ratio versus the reciprocal of pressure. The calculated relationship between water/fuel ratio and the equivalent reduction in gas pressure is shown in Fig. 1 from reference 1. It illustrates, for example, that the injection of equal weights of water and fuel is equivalent to halving the pressure. The method has two advantages: it is the only technique which allows the entire stability loop to be obtained for large flameholders, and any subatmospheric pressure can be simulated while using fan air at atmospheric pressure.

The test facility is now in full operational use and stability loops for flameholders of different sizes and shapes are being obtained as a routine procedure. The initial program of tests was carried out on 30° angle Vee gutters. Several sizes were manufactured in order to provide blockage ratios (gutter csa/duct csa) of 10, 20 and 30 percent. Stability loops were obtained at inlet air velocities of 56, 69, 87, and 117 m/s in a 20 x 15 cm rectangular test section, and at velocities of 23, 30, and 42 m/s in a 30 cm square cross section. Typical stability loops obtained with a 30° Vee gutter of 10 percent blockage, at four different levels of inlet air velocity, are shown in Fig. 3. Logarithmic plots of U_o versus P_e indicate a linear relationship between blowout velocity and pressure ($U_{BO} \propto P_e^{-1}$), as illustrated in Fig. 4 for five gutters of different size and blockage ratio.

At the present time stability loops are being obtained for L-shaped gutters. These gutters are characterized by a "single-sided" flow recirculation in their wake as opposed to a double-sided flow recirculation that is normally associated with conventional bluff-body flameholders. The next phase of rig testing will be devoted to a study of the flameholding characteristics of baffles of irregular shape, in order to determine the "characteristic dimension" of irregular-shaped bluff bodies.

Reference

1. Greenhough, V. W. and A. H. Lefebvre, Some Applications of Combustion Theory to Gas Turbine Development, Sixth Symposium (International) on Combustion, pp. 858-869, 1957.

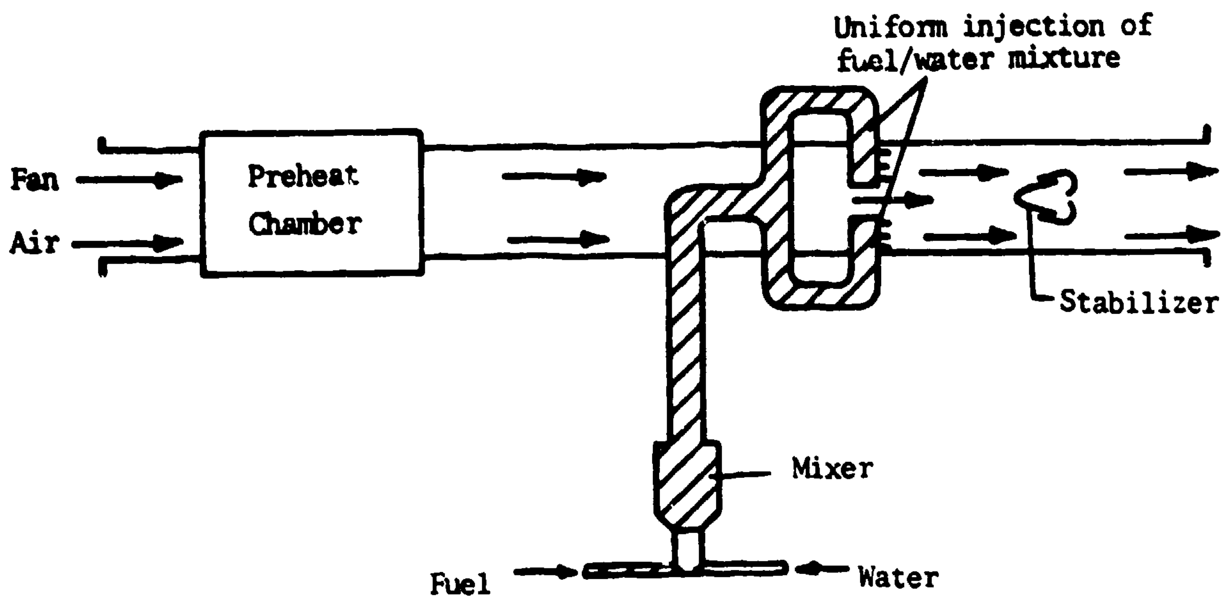

Figure 1. Schematic diagram of test rig

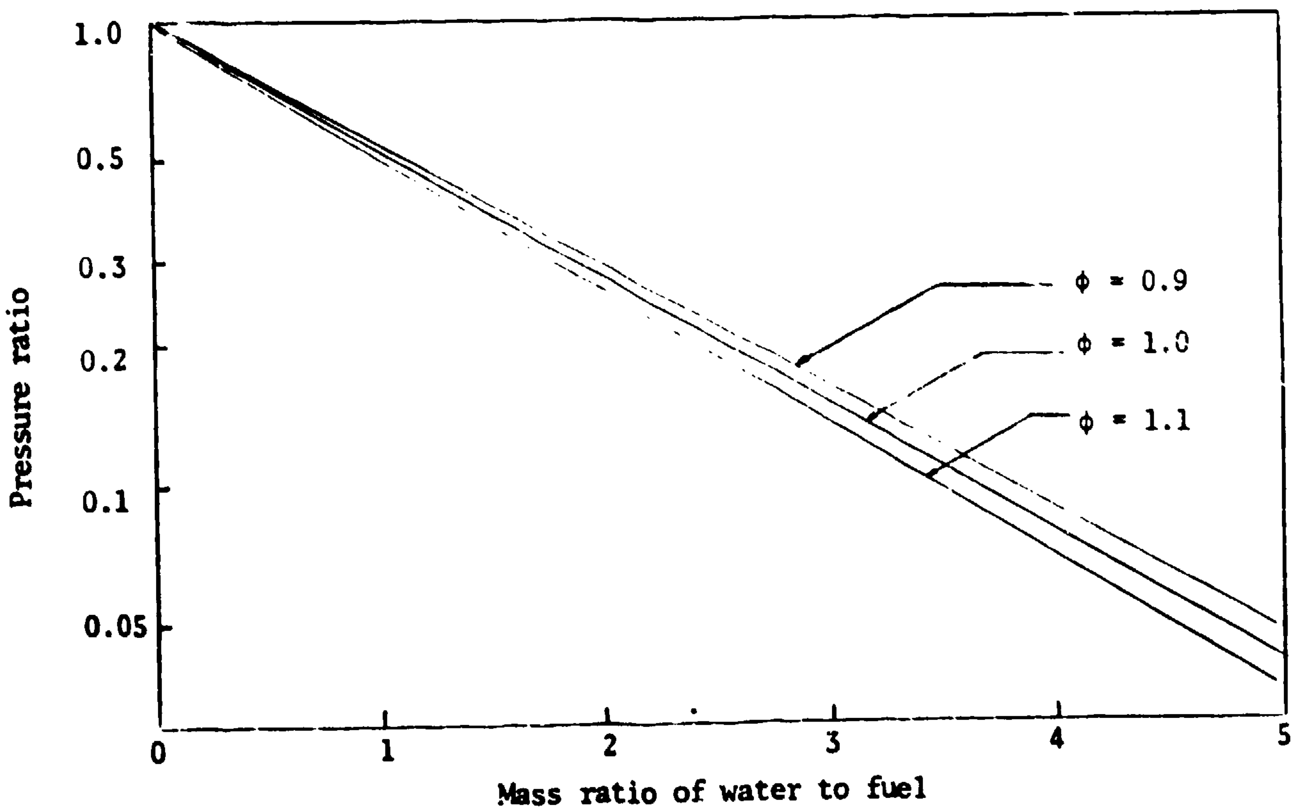

Figure 2. Relationship between water/fuel mass ratio and effective pressure ratio

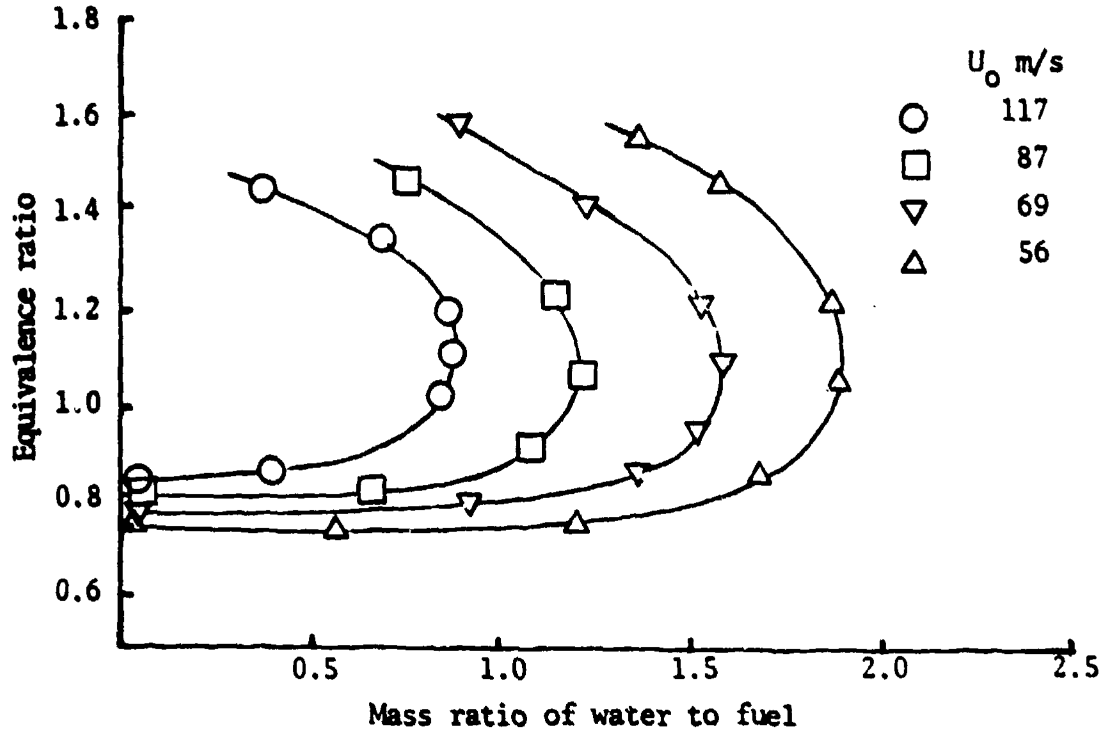

Figure 3. Effect of air velocity on stability limits

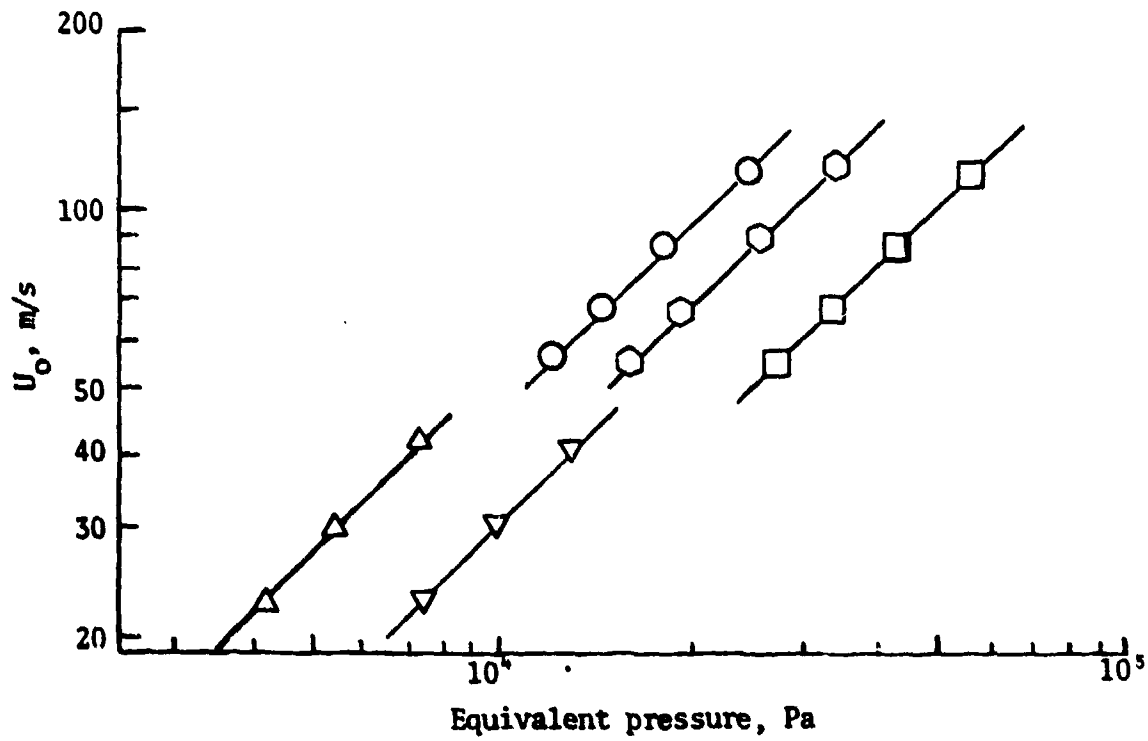

Figure 4. Relationship between blowout velocity and pressure for several 30° Vee gutters

THE IGNITION OF COMBUSTIBLE MIXTURES BY BURNING METAL PARTICLES

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The ignition of combustible mixutres by hot or burning metal particles represents a hazard in many common military activities. Examples are seen in post-crash aircraft fires resulting from mixing of leaking fuel and abraded metal particles [1], or aircraft fires caused by puncture of a fuel tank by an incendiary projectile [2]. Homan and Sirignano [3] found that the minimum ignition energy of methane/air and propane/air mixtures by burning aluminum particles was comparable to, but a bit lower than, spark ignition energies previously reported [4]. Further, the results suggest that the relationships between ignition energy and fuel/air equivalence ratio are similar in ignitions both by sparks and by burning particles. The above points were examined further in this study on the ignition of toluene/air mixtures by burning aluminum particles. The above points were examined further in this study on the ignition of toluene/air mixtures by burning aluminum particles. Not only does the use of toluene provide data on aromatic hydrocarbon, to supplement the existing data on paraffins, but the toluene was examined both as a spray as well as a vapor in mixtures with air.

The technique employed in this study is the same as that described in [3] and sketched in Figure 1. The principal modifications of the technique involve those associated with the fact that the toluene may be introduced as either a liquid spray or as a vapor. The details are given elsewhere [5]. As previously, the technique involves suspending a single particle of aluminum in a large chamber containing the mixture of interest. The particle is suspended on the tip of a glass fibre and is maneuvered into the path of a beam from a Nd/glass laser. The laser is briefly pulsed in order to ignite the particle; the surrounding fuel/air mixture and the glass fibre are essentially transparent at the wavelength of the laser. Hence if ignition of the surrounding fuel/air mixture is to occur, it must receive an appropriate input of energy from the particle. Whether the mixture is actually ignited or not depends upon the particle size, the mixture equivalence ratio and the total amount of energy provided by the laser pulse.

Figure 2 gives the data for various fuel vapor/air mixtures at atmospheric pressure. The trend of the data is the same for methane, propane and toluene. To accomplish this plotting, particle diameters were used to calculate particle masses, which in turn yield energies of combustion per particle. This allows direct comparison of burning particle ignition data with spark ignition data. It is apparent that in all cases the spark data lie at or below the limit of the data for burning particle ignition. This may be viewed as not too surprising, since a spark delivers its energy to the mixture in the matter of microseconds, while it takes several milliseconds for a particle to burn and release its energy. The difference in these time scales reflects a difference in the time available for transport of heat from a potential ignition kernel, the slower process allowing greate time for quenching by heat loss. The minimum in ignition energy for a particular fuel seems to fall at a particular value of equivalence ratio regardless of the nature of the ignition. This suggests that the diffusional stratification mechanism proposed by Lewis and von Elbe [4] for spark ignition may also be applicable for burning particle-type ignitions as well.

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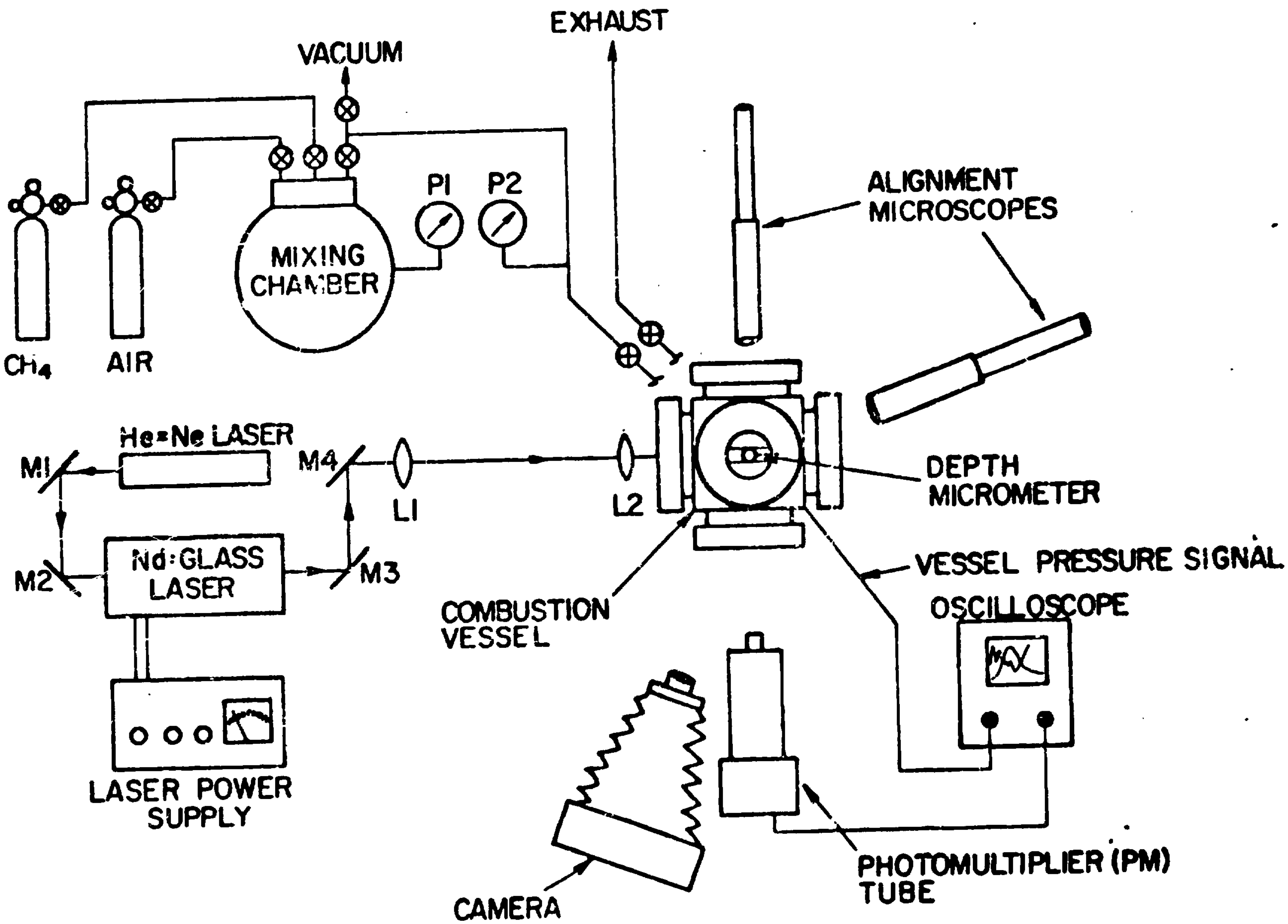
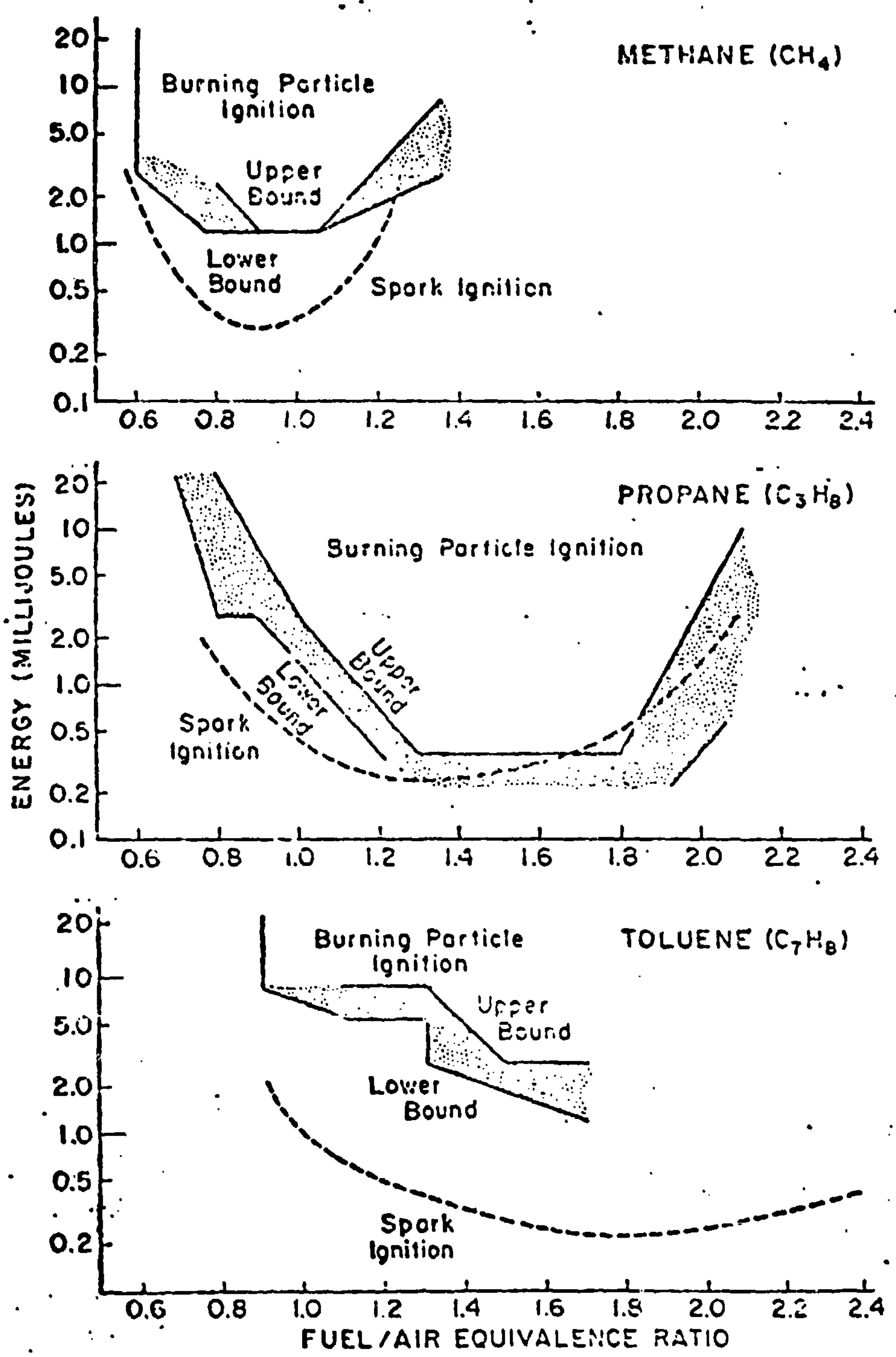
[2] Manheim, J.R., U.S. Air Force APL-TR-73-76 (1973).
[3] Homan, H.S. and Sirignano, W.A., 18th Symposium on Combustion, 1709 (1981).
[4] Lewis, B. and von Elbe, G., Combustion, Flames and Explosions of Gases, Academic Press, pages 334-343ff (1961).
[5] Stanley, T.J., M.S. Thesis, Carnegie-Mellon University, Dept. Chemical Eng., (1981).



SCHEMATIC OF APPARATUS

FIGURE I

FIGURE 2: Minimum Ignition Energies vs. Equivalence Ratios for Methane, Propane and Toluene.



Friday AM Session

8:30 Morning Chairman

J. Manheim
Aero Propulsion Laboratory
AF Wright Aeronautical Laboratories (AFWAL)

8:35 Ignition of Fuels Under High Intensity Laser Radiation

T. Kashiwagi, W. Braun & M. Scheer
National Bureau of Standards, Gaithersburg, MD

9:00 Reactions of Hydrocarbon Gases Initiated by a Pulse Infrared (CO_2) Laser

G.B. Skinner
Wright State University

9:25 AFATL Combustion and Explosion Research and Development Program and Future Requirements Associated with Conventional Weapons

M. Zimmer
AF Armament Test Laboratory/Eglin AFB Florida

9:50 Air Force In-House and Supported Research and Development and Future Requirements in Unconfined Fuel - Air Explosions

G. Parsons
AF Armament Test Laboratory/Eglin AFB Florida

10:15 BREAK

10:30 Research on Detonation Tube Study Analysis of Explosion Phenomena

A. Tullis
Illinois Institute of Technology Research Institute

10:55 Detonation Characteristics of Multiphase Heterogenous Distributed Fuel - Air Clouds

C.W. Kauffman & J.A. Nicholls
University of Michigan

11:20 National Academy of Science Panel on Grain Mill Explosions - Problems, Research Needs and Approaches

C.W. Kauffman
University of Michigan

11:55 LUNCH

Thermal Radiative Ignition of a Liquid Fuel

Takashi Kashiwagi
Thomas Ohlemiller

National Bureau of Standards
Washington, D. C. 20234

High power lasers are now being developed as tactical weapons. Such lasers pose a threat to aircraft integrity by ignition of jet fuel and subsequent fire or explosion. A fundamental understanding of the mechanism of the ignition will help provide design guidelines for the improvement of aircraft survivability. However, the level of understanding of radiative ignition of liquid fuels is currently limited to little more than knowledge of ignition delay times for limited sets of conditions. Therefore, the aim of the present program in FY 81 has been; (1) to develop a technique for simultaneous measurements of temperature and concentration distributions in the gas phase during the pre-ignition period due to laser irradiation on a liquid fuel surface; (2) to deduce from this data the key processes which determine the ignition behavior.

Conventional techniques using a thermocouple and a sampling probe to measure these distributions are not effective due to their slow time response and point by point nature. In this study, a two-wavelength holographic interferometry technique has been developed. Red light (He/Ne laser) and blue light (Ar ion laser) interferograms are superimposed on each frame of a high speed movie ($\leq$ 500 frames/sec). The change in refractive index in the gas phase above the irradiated liquid is influenced by temperature and concentration changes simultaneously; from a knowledge of these dependencies and the fringe shifts at both wavelengths, the temperature and concentration fields can be calculated. The high-speed movie thus reveals the time-dependent evolution of these fields. The system is illustrated in Fig. 1. The movies cover the period extending from just before the CO_2 laser irradiation starts until a flame propagates through the flammable mixture of gases from the initial ignition location. 1-Decene was used as the liquid fuel. A typical series of pictures is shown in Fig. 2.

The effects of incident laser radiant flux and oxygen concentration in the gas phase on the distribution of temperature and vapor concentration and on the location of first appearance of flame were studied. It is found that the fuel vapor temperature away from the surface is higher than that near the surface even in a nitrogen environment. This implies that the absorption of the incident CO_2 laser radiation by the fuel vapor is the key process to raise the gas phase temperature and initiate gas phase chemical reactions. Comparison between the nitrogen and air environments indicates that the temperature and fuel vapor concentration distributions show significant differences which indicate a contribution from exothermic chemical reactions at an early stage of the pre-ignition period. The location of the appearance of first flame does not change significantly with an increase in incident laser flux but it tends to become nearer to the surface with an increase in oxygen concentration in the gas phase.

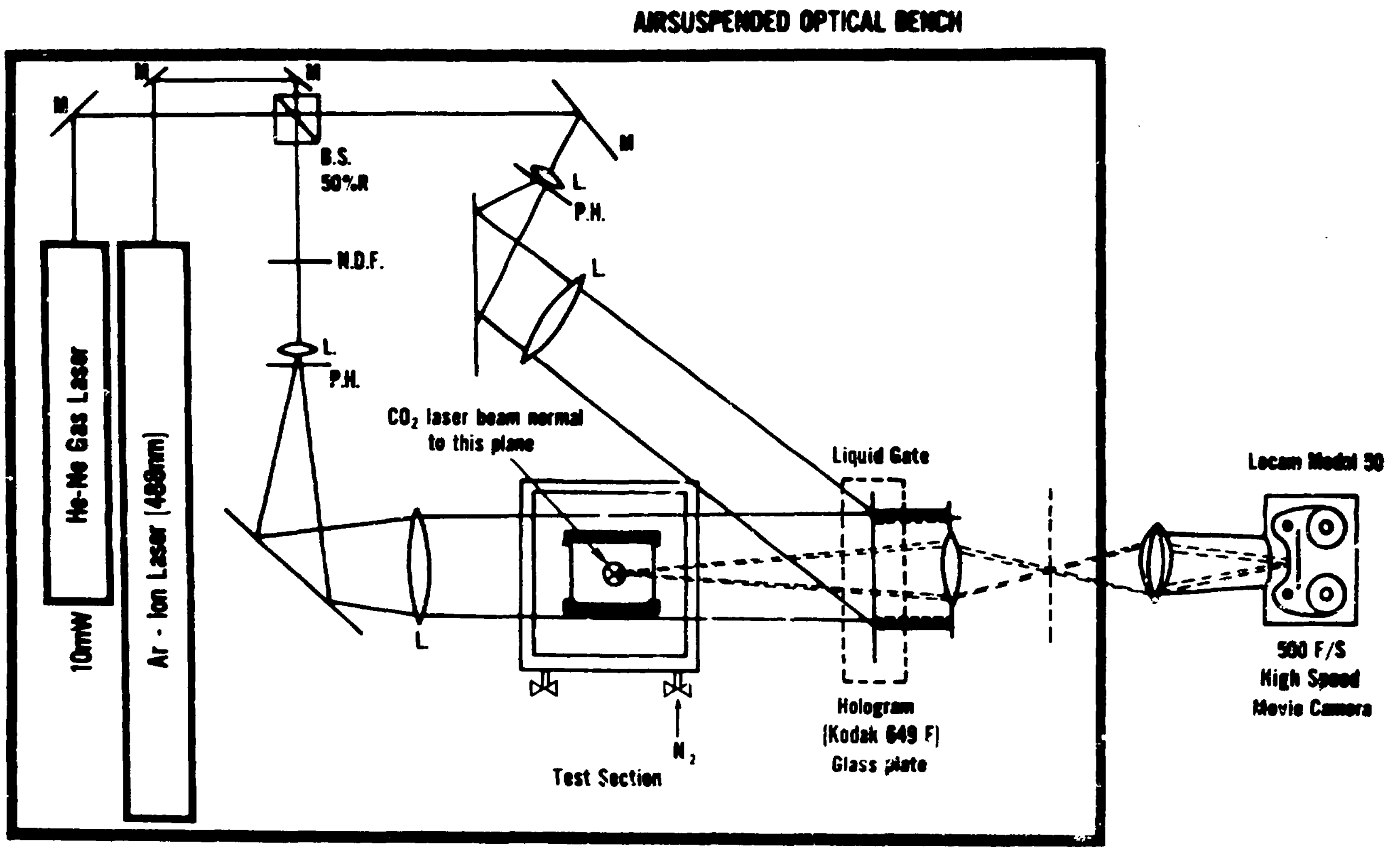


Fig. 1. Schematic illustration of holographic interferometry.

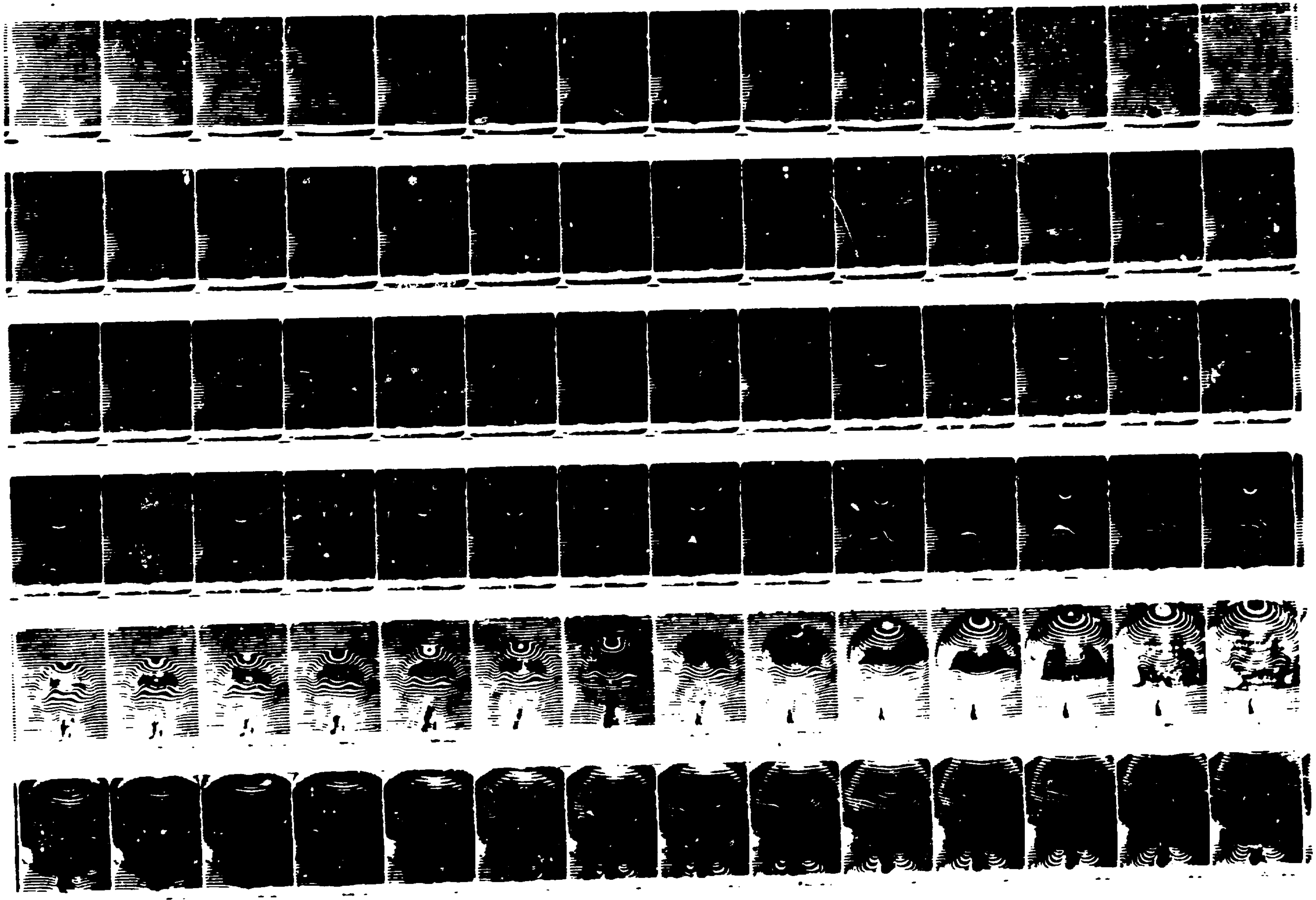


Fig. 2. Interferometric movie picture of 1-decene at CO_2 laser flux of 260 W/cm^2 with air, 500 f/sec.

Ignition of Fuels by High-Intensity Laser Radiation

Suresh C. Khandelwal and Gordon B. Skinner
Department of Chemistry
Wright State University
Dayton, Ohio 45435

The initial goal of this program was to find whether a burst of radiation from a pulsed infrared laser would be more likely to cause ignition of hydrocarbon fuels more readily than addition of the same amount of energy from more conventional sources. As an energy source we used a CO_2 TEA laser which emitted up to 100 J of energy over an area of 100 cm^2 during a time of less than a microsecond (50 J within about 70 nanoseconds and the balance mostly within the following 500 nanoseconds). The radiation, of wave length 10.6 µm, could be focussed using NaCl lenses.

We found that at gas pressures of a few torr up to one atmosphere, propane molecules do not undergo decomposition, and propane-air mixtures do not ignite, via multiphoton absorption processes up to a laser fluence of 40 J/cm^2 (400 MW/cm^2). At higher fluences plasma is formed, which causes extensive reaction. If the radiation strikes an aluminum surface in contact with propane the molecules dissociate at the low energy fluence of 2 J/cm^2 (20 MW/cm^2). This is considered due to plasma formation in the propane near the laser radiation-aluminum interface. Since the absorption coefficient of propane at 10.6 µm is higher than those of most other saturated aliphatic hydrocarbons, it seems that the possibility of homogeneous ignition of fuel-air mixtures by infrared laser radiation in an aircraft is very unlikely, compared to heterogeneous processes.

During the past year our work has progressed in a different direction, namely, using the laser to determine both reaction kinetics and thermal conductivities of polyatomic molecules at high temperatures and low pressures. Since, as a result

of our work and other concurrent studies, it is clear that at pressures of 1 to 100 torr our laser irradiated samples reach thermal energy equilibrium (i.e. equilibration among vibrational, rotational and translational energies) before significant chemical reaction occurs, then we can measure kinetics by determining the extent of reaction in an irradiated sample as a function of the energy of the laser pulse. One quantity needed in the calculation is the thermal conductivity of the sample, which may or may not be known, but this can also be determined by measuring the pressure history of the sample in separate experiments at slightly lower temperatures.

The method we have developed seems very promising for measurement of these two quantities. It is clear from the literature that few measurements of thermal conductivities of polyatomic molecules exist at high temperatures. Our method can be used for either pure gases or mixtures, and in terms of stability requires only that molecules be stable for about 50 milliseconds at the highest temperature involved. Therefore thermal conductivities of combustion gases can be made nearly up to the temperatures at which reactions occur. If the gases of interest do not absorb the laser radiation, a small amount of an absorber, such as SF_6, for which the thermal conductivity is known, can be added. The result of these measurements is an equation for the thermal conductivity, that can be used to make an extrapolation into the temperature range where reaction occurs.

The literature also shows that little information on unimolecular reactions, many of which are important in combustion, is available at high temperatures and low pressures. Much of the high temperature data has been determined in shock tubes, where pressures are usually (although not always) above one atmosphere. The laser irradiation method has given us data down to the range of 1 to 5 torr, so that if these data are combined with those from shock tubes, a total pressure range in the neighborhood of 10^3 is possible. The present method also allows use

of 100% or nearly 100% of reactant gas in the sample, which cannot be done in most shock tube or flame experiments.

These experiments are now being carried out in two prototype reaction systems. In one, the compound CF_2H-CH_3, which absorbs strongly at 10.6 μm, is being studied by itself and in mixtures with He and Ar. In the other, cyclopropane is being used as a hydrocarbon reactant, with SF_6 as absorber. Data are analyzed by a computer model of the system.

It should be pointed out that there are a number of methods of predicting both thermal conductivity of gases and the effect of pressure on the rate constants of reactions. However, these methods are semi-empirical in nature and are not highly dependable outside the ranges in which they have been tested by experimental data. By using our method to obtain experimental data for a few substances, it will be possible to validate and/or modify the prediction methods so they can be used with greater confidence over a wider range of conditions.

AFATL COMBUSTION AND EXPLOSION RESEARCH AND DEVELOPMENT PROGRAM AND FUTURE REQUIREMENTS ASSOCIATED WITH CONVENTIONAL WEAPONS

Dr. M. Zimmer
AFTL/DLJW
Eglin AFB FL

ABSTRACT NOT AVAILABLE

AIR FORCE IN-HOUSE AND SUPPORTED RESEARCH AND DEVELOPMENT AND FUTURE REQUIREMENTS IN UNCONFINED FUEL - AIR EXPLOSIONS

Dr. G. Parsons
AFATL/DLJW
Eglin AFB FL

ABSTRACT NOT AVAILABLE

CHARACTERIZATION OF IGNITION IN SOLID FUEL-AIR EXPLOSIVES (FAE)

A.J. Tulis, R.H. Snow, and S. Chandra
IIT Research Institute
10 W. 35 Street
Chicago, Illinois 60616

Abstract

The ignition mechanism of solid fuel-air explosions has not previously been elucidated. Mechanisms such as droplet breakup, which can occur with liquid fuels, are not expected with solid fuels. This paper describes both analytical and experimental investigations on solid fuels in progress at IIT Research Institute.

The analytical investigations focused attention on the heat transfer to individual particles while they are exposed to the high-temperature and high-pressure conditions of the adiabatic shock-compression region that is associated with a propagating detonation. Surface temperatures are calculated as a function of particle size and compared with those necessary to initiate chemical reaction. Radiation heating is found to be unimportant except for the smallest particles. Convective heat transfer raises the surface temperature to 600 to 1000°K within an induction zone between the incident shock wave and the subsequent reaction front. This points out the significance of extended induction zones that occur with two-phase detonations.

The experimental portion of this effort has measured this induction time, as well as the detonation velocities and pressures. The measurements were carried out in a detonation tube. The experimental materials consisted of such solid powder fuels as aluminum, starch, coal and plastics. The parameters under study are particle size, concentration, initiation source, coatings, and other factors. Data obtained so far confirm the magnitude of the predicted induction times.

DETONATION CHARACTERISTICS OF SOME DUSTS AND LIQUID-DUST SUSPENSIONS (AFOSR-79-0093)

J. Arthur Nicholls, C. William Kauffman, Martin Sichel

Department of Aerospace Engineering
The University of Michigan
Ann Arbor, MI 48109

The aim of this research is to determine the detonation properties of high explosive dusts when dispersed in air under unconfined conditions. Theoretically, such dusts have the potential for producing very high pressures but experimental confirmation, under well controlled conditions, is required. Accordingly, a combined experimental and theoretical study is being conducted so as to obtain the desired results and understanding.

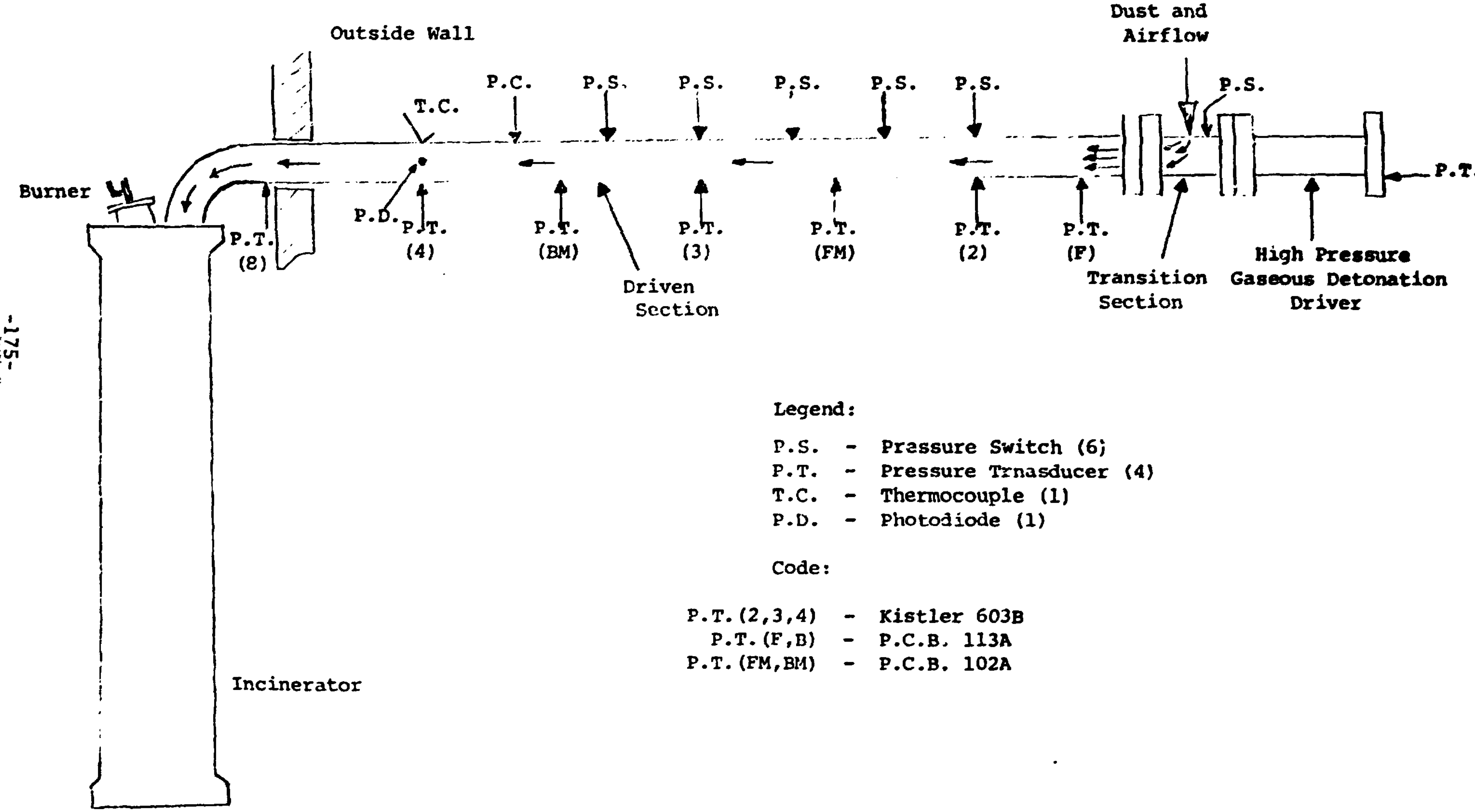
For this purpose, a special shock tube facility has been designed, constructed, and operated. The facility is shown in Fig. 1.

Dust is introduced into a transition section and then blown downstream through a long driven section by a suitably high air flow. A strong shock wave, generated by the explosion of H_2/O_2 in the driver section, ignites the dust-air mixture. The subsequent wave propagation is monitored so as to determine whether detonation is achieved. Measurements made include pressure, velocities, and light emission. Photographic records are also obtained.

Experiments have been conducted using small plastic coated particles of RDX-E (about 10 μm) as well as relatively large plastic coated particles of RDX-A (about 150 μm). Surprisingly, the small particles did not lead to detonation, even when the air was enriched with oxygen. The larger particles did appear to result in detonation when some oxygen enrichment was used. The difference is believed to be attributable to the lower acceleration of the large particles behind the shock and hence higher rate of heat transfer to the particles.

Streak photographs have been obtained and reveal some of the details of the dust particle dynamics behind the shock. Some experiments were conducted with RDX in nitrogen. Ignition did occur, but much further behind the shock wave and the wave strength decayed continuously with distance. Other experiments planned include the case where the RDX-E dust is mixed in with a liquid fuel (such as decane). For these experiments an existing vertical detonation tube would be used.

On the analytical side, the Chapman-Jouguet detonation properties for RDX dust in air as well as RDX mixed with other liquid fuels have been calculated. Also, a numerical code has been used to study the initiation of detonation by a strong blast wave in various dust-air and decane droplet-oxygen mixtures. The effects of particle and droplet loading and reaction zone length on the initiation process have been considered. Also, the structure of the reaction zone has been examined.



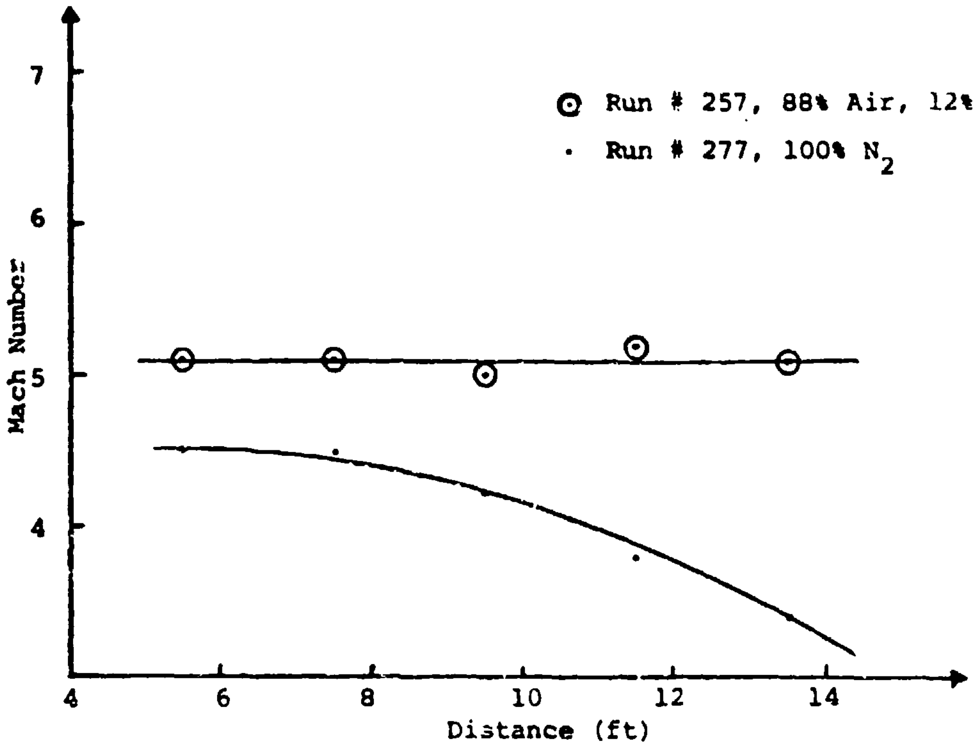
Legend:

P.S. - Prassure Switch (6)
P.T. - Pressure Trnasducer (4)
T.C. - Thermocouple (1)
P.D. - Photodiode (1)

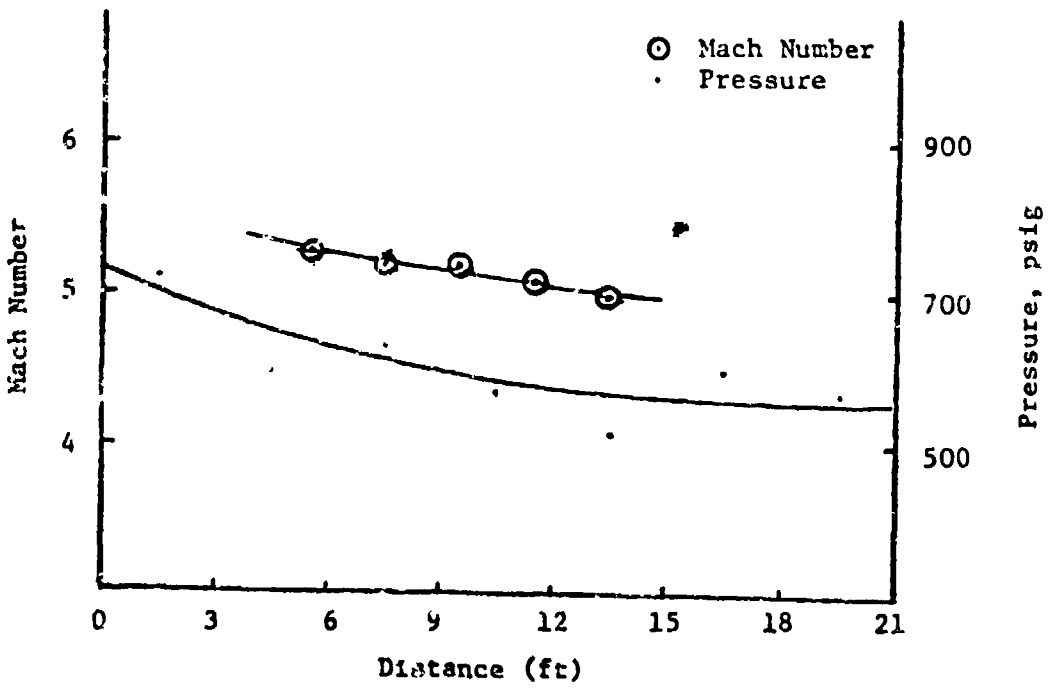
Code:

P.T.(2,3,4) - Kistler 603B
P.T.(F,B) - P.C.B. 113A
P.T.(FM,BM) - P.C.B. 102A

Figure 1. Schematic of Experimental Set-up



Wave Mach Number, RDX-A, 1300 gm/m^3,
Driver Pressure 119.3 psia, 1/4 Driver.



Wave Mach Number and Pressure, RDX-A,
Run #292, 1300 gm/m^3, 100% O_2, Driver
Pressure 119.3 psig, 1/4 Driver.

HAZARDS OF AGRICULTURAL DUST EXPLOSIONS

C.W. Kauffman
Department of Aerospace Engineering
The University of Michigan

In the United States during 1980 there were 44 dust explosion incidents in grain handling facilities. These resulted in 10 deaths, 51 injuries and an unknown amount of property damage. World wide in 1980 five explosions were reported resulting in 7 deaths and 42 injuries. Thusfar during 1981 (mid-April) there have been 7 explosions resulting in 9 deaths and 34 injuries and the loss of a major export elevator. During an eight-day period at Christmas of 1977 five domestic grain elevator explosions occurred resulting in 59 deaths, 48 injuries, and extensive property damage. In that this series of explosions resulted in the loss of 2½ % of all United States export elevators and the death of five Federal employees prompt action was taken by Federal authorities in order to prevent future occurrances. In July 1978 an International Symposium on Grain Elevator Explosions was sponsored by the United States Department of Agriculture in Washington, D.C. in order to review the dust explosion literature in this context. In November 1979 the National Academy of Sciences incorporated the Panel on the Causes and Prevention of Grain Elevator Explosions to suggest specific safety actions and to investigate serious accidents. For the past 2½ years this activity has occurred, and it will terminate in July 1981. This panel has already issued one report relating to the desirability of investigating all future major accidents (as is the case for transportation accidents), and it will issue two more reports, in the summer of 1981, one relating to the general topic of grain elevator hazards, and the other devoted to the techniques of grain elevator dust control.

During the period of its tenure the Panel has thus far investigated 14 serious accidents. These have occurred at small country elevators having a capacity of 1×10^4 bushels, in large inland elevators with a storage capacity of 1.5×10^6 bushels, and at a large export elevator with a capacity of 6×10^6 bushels and a large throughput capacity. These investigations have shown that the sequence of events leading up to an accident can almost always be clearly identified although traditionally the majority of elevator accidents have been attributed to unknown causes. The usual safety philosophy of attempting to control ignition sources has been shown to be quite ineffective. Although welding and cutting have indeed become less frequent ignition sources others have surfaced. The most positive method for the prevention of dust explosions in grain elevators would be to remove the fuel. This may be done effectively with various dust control systems, i.e. intermittent sweeping on flat surfaces, intermittent blow down of elevated surfaces, continuous cleaning of the grain, or the continuous application of suction at critical locations. The bucket elevator appears as the cause or a participant in an inordinate number of elevator accidents. This occurs for two reasons. First, the suspended dust concentration usually exceeds the lower explosive limit. Second, numerous ignition sources may be present, e.g. tramp metal, rubbing belt and buckets, static electricity, etc. The failure of the bucket elevator casing may then act as a very positive ignition source for secondary explosions.

Observation of some explosion damage has caused a reexamination of the detonation of dust/air mixtures. Certain dusts — wheat and oats — have been found capable of detonating. These dusts also show the shortest ignition delay time when struck by an incident shock wave. The apparent cause for the difference in combustion behavior between the different dusts is the ballistic coefficient. For material with relatively well known

combustion chemistry — coal — an analytical model of ignition has been developed. Because of the large length to diameter ratios with numerous turbulence generating obstacles which are present within grain elevators the possibility of detonations may not be excluded. In this situation venting is not an effective safety precaution.

Unless the government, industry, and labor indeed recognizes the potential hazard of a thin layer of grain dust —perhaps as little as 0.4 mm — grain elevator accidents will contiune to occur.

Friday PM Session

1:30 Afternoon Chairman

G. Parsons
AF Armament Test Laboratory - Eglin AFB Florida

1:35 Mechanisms of Direct Shockless Initiation of Unconfined Fuel - Air Detonations

J. Lee, R. Knystautas, I. Moen & C. Guirao
McGill University - Canada

2:00 Detonation Initiation and Propagation in Chemically Sensitized Unconfined Fuel - Air Mixtures

G. Von Elbe, E.T. McHale, R. Fry
Atlantic Research Corporation

2:25 Ignition, Acceleration, Stability and Limits of Detonation

H. Wagner & W. Jost
University of Gottengen

2:50 Effect of Concentration Gradients and Variable Reaction Kinetic Rates on Detonation Properties of Distributed Reactive Fuel - Air Clouds

H. Edwards
University of Wales - England

3:15 BREAK

3:30 Ignition Combustion, Detonation and Quenching of Flames and Detonations in Reactive Mixtures and Related Phenomena

R. Edse
Ohio State University

3:55 Theoretical Modeling and Prediction of Detonation Properties in Dispersed Powdered High Explosive - Air Clouds

K. Frair
Virginia Polytechnic and State University

4:20 Accidental fuel air Clouds, then Shapes and Burning Properties

D. Lewis
England

4:45 ADJOURN

Study of the Fundamental Mechanicsms of
Unconfined Detonation in Fuel-Air Explosion

by

John H.S. Lee and Rom Knystautas
Dept. of Mechanical Engineering
McGill University
Montreal, Canada

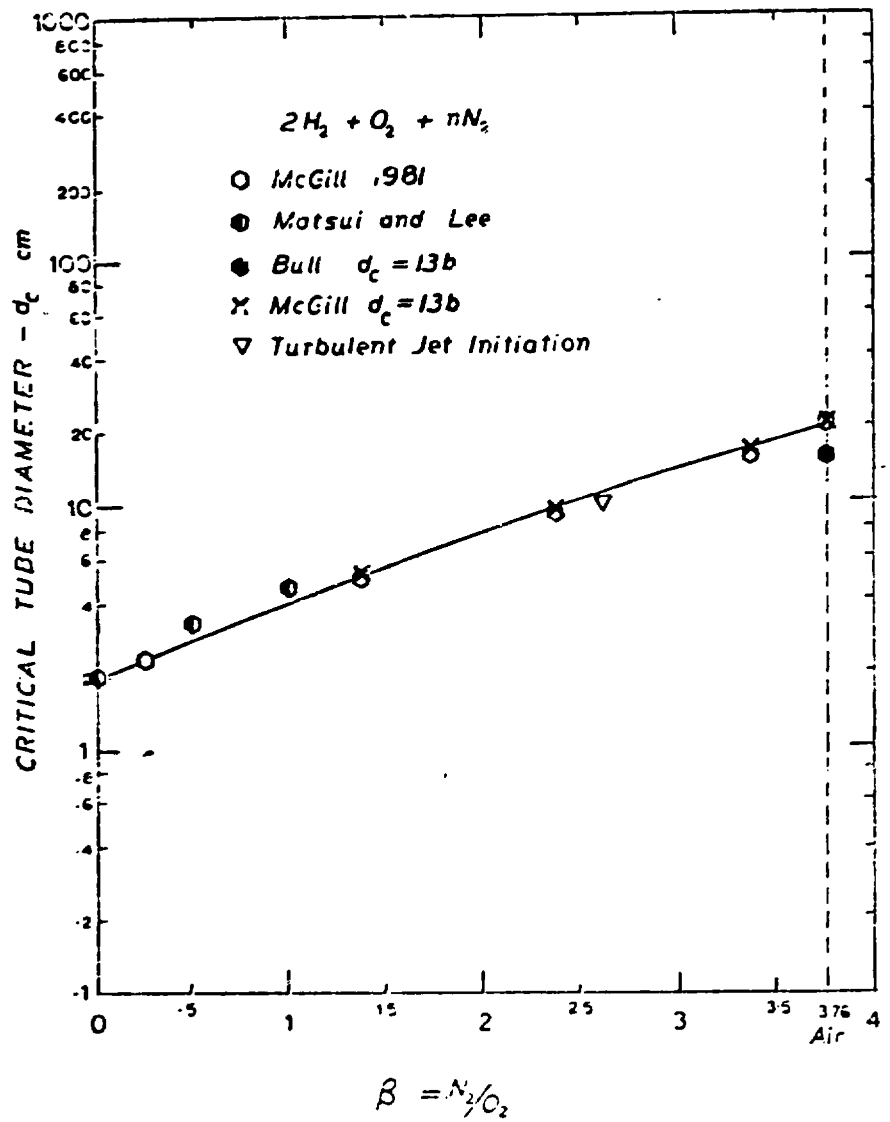
ABSTRACT

Conventional means of direct initiation of Fuel-Air Explosive (F.A.E.) is via a charge of high explosive (H.E.). The primary aim of our research program is to investigate the so called "shockless" initiation mechanism where the spontaneous formation of the detonation is achieved via the rapid mixing of a chemical initiator (or sensitizer) with the explosive mixture. Whereas conventional blast initiation with an H.E. charge can always be effected simply by increasing the charge weight, the chemical or shockless initiation scheme requires a rather precise combination of the mixing rate with the characteristic chemical reaction times of the primary initiator-fuel (or oxygen) reaction to produce the necessary free radicals for initiation and the secondary main explosive reaction of the oxidation of the fuel itself. The turbulent mixing time on the other hand is critically dependent on the dimension of the mixing zone required. Any attempt to increase in mixing rate implies an increase of the entrainment of the turbulent jet and hence a reduction of its ability to penetrate into the explosion mixtures resulting in a smaller mixing zone. It is found that the critical mixing zone dimension depends on the sensitivity of the mixture. While the size of minimum size of the mixing zone or initiator volume decreases with the increase in the sensitivity of the F.A.E., the mixing rate required also goes up to compensate for the increase in sensitivity and the shorter chemical times involved. Thus the key fundamental parameter for the problem is the minimum dimension of the initiation zone required for a given fuel air mixture and the minimum turbulent mixing rate required for a given combustion of fuel-air mixture and the chemical initiator (or sensitizer) used for the initiation process. Our efforts for the past two years have been primarily devoted to i) the establishment of the minimum dimension of the mixing zone required for detonation initiation by turbulent mixing and ii) for the particular case of using hot combustion product gases as the chemical initiation agent, the determination of the critical mixing rate (turbulent scale and intensity) required for the initiation.

An important result obtained is the discovery that the minimum diameter of a turbulent jet of hot combustion products required for direct initiation via rapid mixing is about the same as the critical tube diameter of

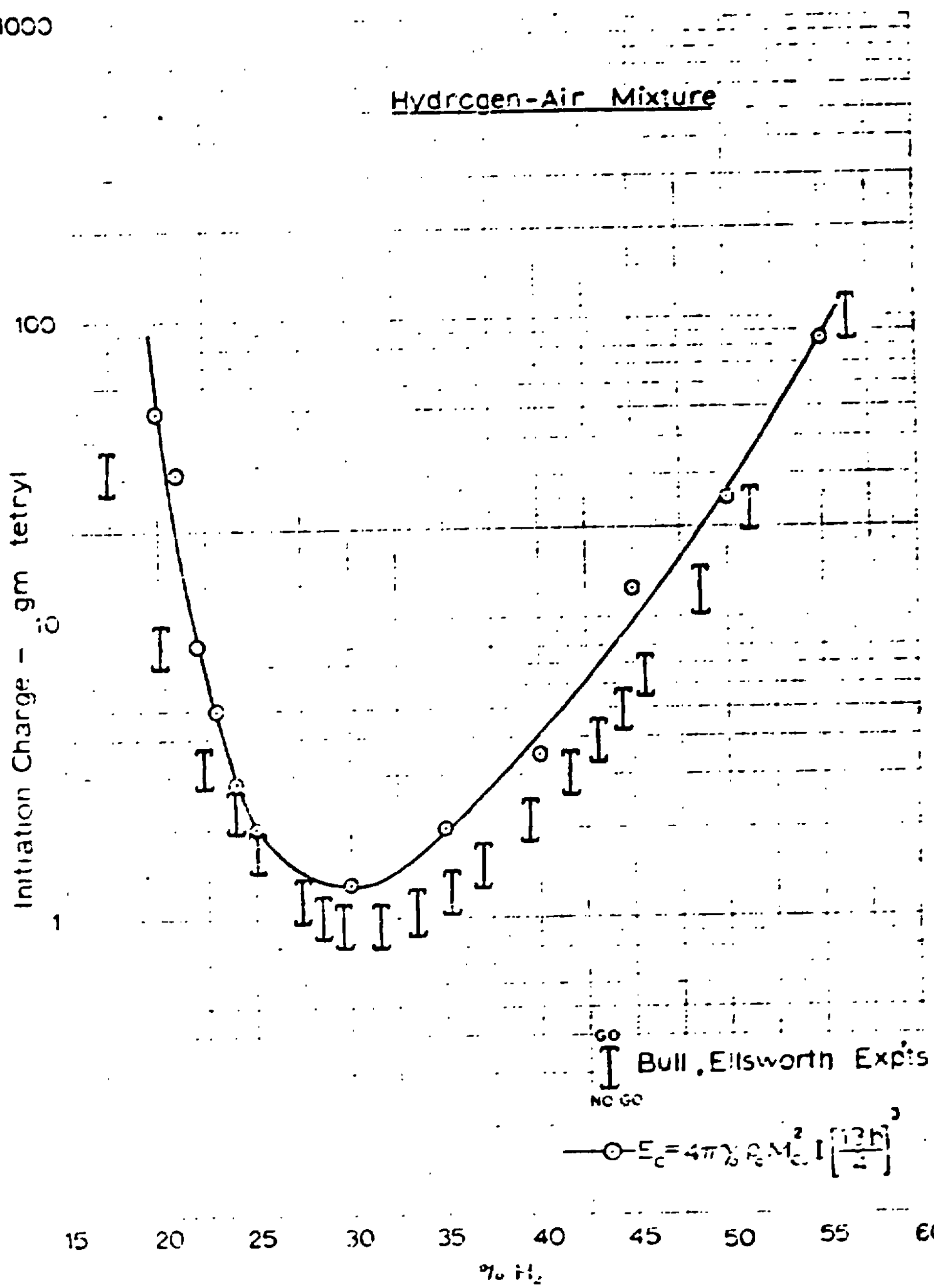
the explosive mixture itself. The critical tube diameter being the minimum diameter in which a planar detonation established in the tube can exit into unconfined medium and subsequently initiate a spherical detonation there. Fig. 1 shows the critical tube diameter for H_2-O_2-N_2 mixtures and successful turbulent jet initiation using a gridplate with holes of about 5 mm square. Thus, considerable efforts have been expended in the past two years to establish this critical diameter for various F.A.E. under different chemical compositions both inside laboratory where possible (i.e., for more sensitive fuels and for oxygen enriched fuel-air mixtures) and large scale field tests for the less sensitive fuel-air mixture and for off-stoichiometric mixtures. With enrichment, the critical tube diameter for the following fuels (C_2H_2, H_2, C_2H_4, C_2H_6, C_3H_8, MAPP, C_3H_6, C_4H_{10}, CH_4) have been established while off-stoichiometric mixtures for the C_2H_2-air and C_2H_4-air have been investigated in larger scale field tests in collaboration with CMI (Christian Michelsen Institute) and FBT (Defense Construction Services) in Norway, and DRES (Defense Research Establishment Suffield, Canada). Of primary significance is the establishment of an empirical law relating the critical tube diameter "d_c" of the explosive mixture with the cell diameter λ of the detonation wave in the mixture (i.e., $d_c \simeq 13\ \lambda$). An extensive program of measurement of the detonation cell diameter has been carried out and thus far it appears that the empirical relationship of $d_c = 13\ \lambda$ is valid. Thus we may now correlate the cell diameter to the minimum dimension of the mixing zone required for chemical initiation. Further correlation of the cell diameter with the critical energy (or charge weight) for combustion blast initiation enables the fundamental linkage between cell diameter, critical energy, critical tube diameter, minimum dimension of the mixing zone for chemical initiation to be established. Fig. 2 shows the correlation between critical tube diameter, cell size and initiator charge weight for blast initiation for H_2-air mixtures. The cell diameter of self-sustained detonation is fundamentally related to the characteristic chemical (or induction and recombination times) of the mixture. Thus, we feel that link between fundamental chemical parameters of an explosive to the detonation properties can now be established at least on a semi-empirical basis.

To investigate the mixing rate required for chemical initiation using the combustion products or the mixture itself as the chemical agent, the experiments are performed in tubes with repeated obstacles to generate a highly turbulent mixing zone at the interface between an accelerating turbulent flame brush and the unburned gases ahead of it. In essence, the experiment is similar to the classical experiments of transition from deflagration to detonation in tubes except repeated obstacles are placed in the tube to generate the desired turbulent scales. Measurement of the flame speed and turbulent parameter of the turbulent mixing zone at the flame brush at the onset of transition permits the determination of the mixing rates and turbulent scales and intensities required for initiation. Experiments have been carried out in tubes of various diameters and to achieve an understanding of the scaling laws required for turbulent mixing, large scale experiments have also been carried in a 2.5 m diameter tube in Norway. Results of these mixing experiments will also be discussed.



CRITICAL TUBE DIAMETER - d_c cm
$2H_2 + O_2 + nN_2$
McGill 1981
Matsui and Lee
Bull $d_c = 13b$
McGill $d_c = 13b$
Turbulent Jet Initiation
$\beta = N_2/O_2$
Air

FIG·1



Hydrogen-Air Mixture
Initiation Charge - gm tetryl
% H_2
GO
NO GO
Bull, Ellsworth Expts

FIG·2

Chemical Initiation of FAE Clouds

Guenther von Elbe, Edward T. McHale and Ronald S. Fry
Principal Ingestigators

Atlantic Research Corporation
Alexandria, Virginia

This study deals with the blast effect of an FAE cloud that is obtained by dispersing a liquid fuel such as heptane simultaneously with an agent such as ClF_3 (CTF) or BrF_3 (BTF). The processes in an FAE cloud of this kind are complex and an objective of the present study is to obtain experimental data to permit the modeling of the blast mechanism from existing theories of combustion, detonation, and fluid mechanics as is done for conventional second-event FAE initiation. An understanding of the blast mechanism that leads to model concepts is necessary for scaling relations.

The test bomb used in the current experiments is shown in Figure 1. Heptane is confined between two massive steel blocks in a 120° segment of a cylindrical wafer. Stainless-steel containers of CTF or BTF are inserted in the recesses of the star-shaped dispersing charge of RDX. The liquids are dispersed in a ray pattern of jets which ignite and expand explosively, thus entraining the air that is entrapped between the jets. Experiments were performed at 1 in, 2 in and 4 in separation of the steel blocks corresponding to 0.3 lbs, 0.6 lbs and 1.2 lbs heptane, keeping the agent (CTF) at 0.1 lbs and RDX at 0.2 lbs. With 0.3 and 0.6 lbs heptane, the initial fuel/CTF explosion was followed by the development of a rapidly burning fire ball of heptane and air, whereas with 1.2 lbs the heptane ignition was quenched. Figure 2 shows a record of the pressure inside the fire ball at 0.6 lbs heptane. Burn-out of the fuel occurs in about 0.1 second and generates a pressure of about 5 atmospheres; this is followed by alternate rarefaction and recompression in a bubble oscillation that extends to estimated distances of the order of 100 feet. Other records (not shown) give the structure of the pressure history at the peak value near 5 atmospheres.

The burn-out time is primarily determined by chemical kinetics. The mixture of hydrocarbon and air attains temperatures above about 900°C at which hydrogen release becomes significant and the chain-branching reaction between hydrogen and oxygen becomes controlling. Since the reaction rate is accelerated by compression, a chance pressure wave may develop into a detonation wave. This does not occur at the small scale of the present experiments but might occur if the scale were increased from 0.6 lbs to, say, 100 to 1000 lbs of fuel. Accordingly, any future experiments should be conducted at a greatly increased scale.

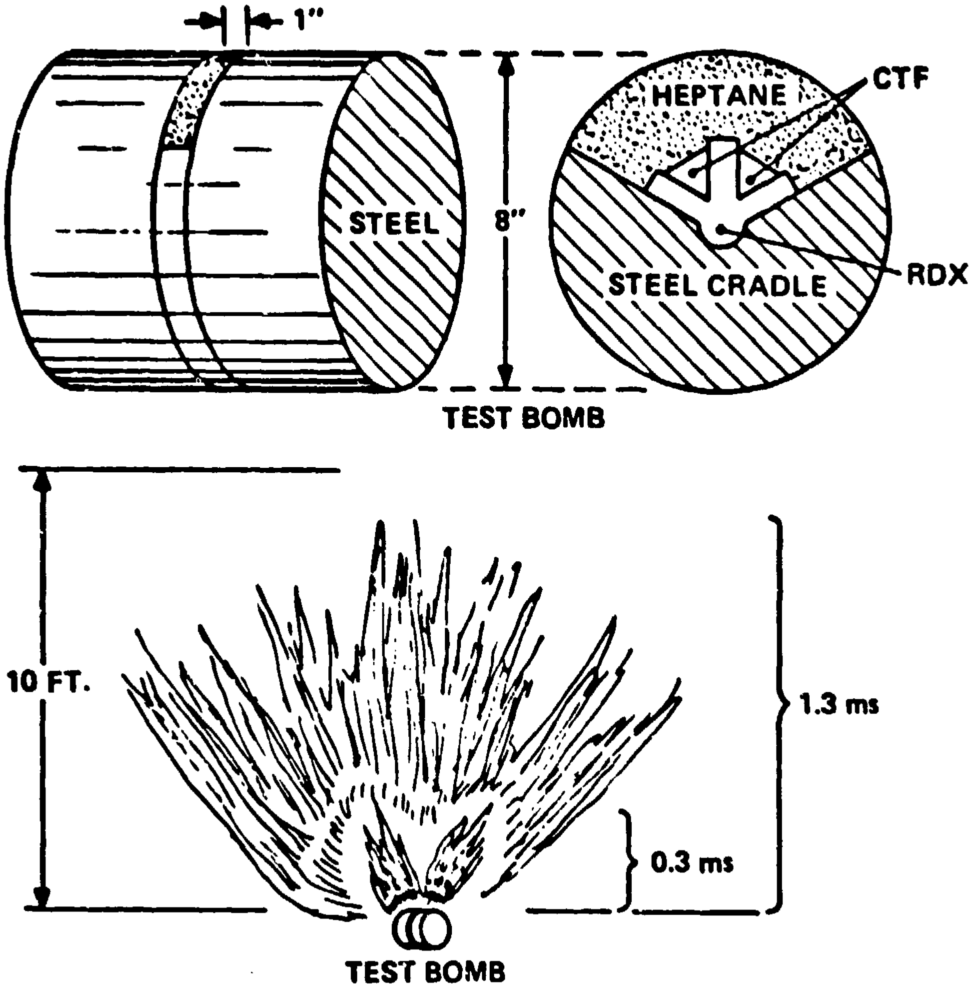


Figure 1. Test Configuration and Ray Pattern of the FAE Cloud

A shaped RDX charge is used to obtain deep and rapid penetration of the ambient air by jets of liquid fuel (heptane) and igniting agent (CTF). No ignition occurs without the igniting agent.

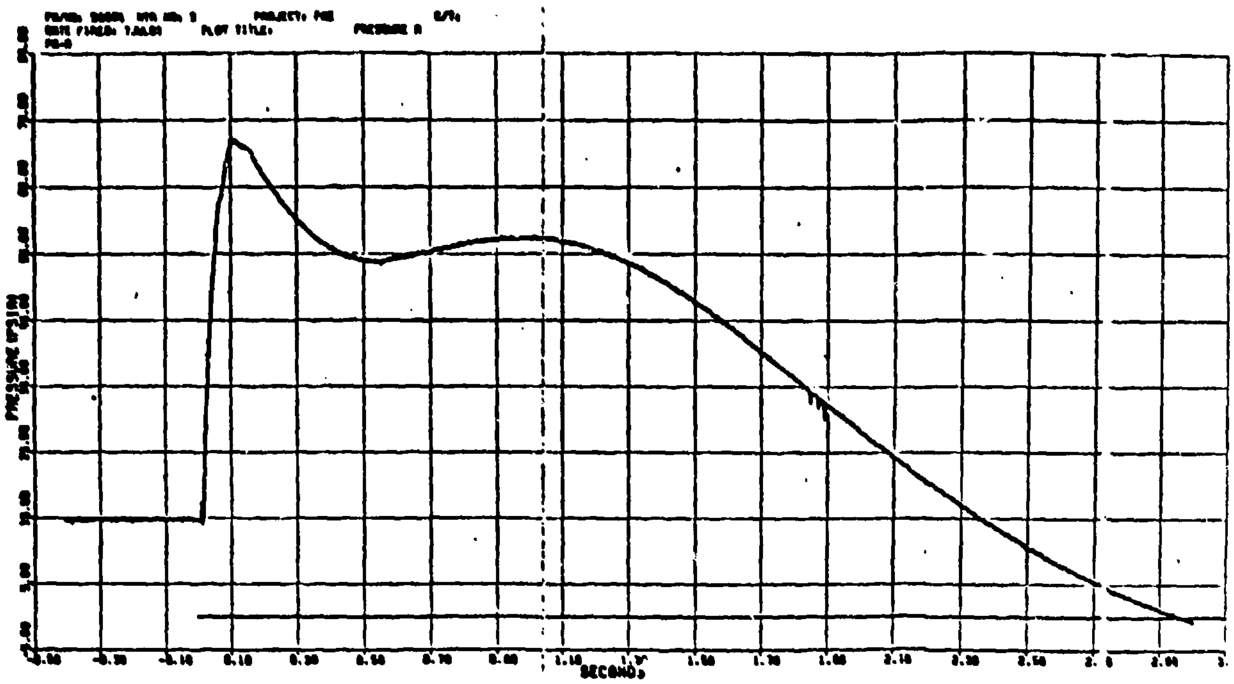


Figure 2. Pressure Record in Center of FAE Cloud. Fuel (Heptane): 0.6 lbs; CTF: 0.1 lbs; RDX: 0.2 lbs (Not Optimized).

Air entrainment and combustion is complete in about 0.1 second.

Pressure rise to about 5 atmosphere is followed by alternate rarefaction and recompression (bubble effect).

Bubble radius is of the order of 100 feet.

In a full-scale system (100 lbs - 1000 lbs fuel) the cloud is expected to detonate.

IGNITION, ACCELERATION, STABILITY AND LIMITS OF DETONATION

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ABSTRACT NOT AVAILABLE

THE BEHAVIOUR OF DETONATION WAVES IN SINGLE PHASE HETOROGENEOUS SYSTEMS

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The present research is aimed at investigating the interaction of detonation waves with gaseous interfaces. In unconfined fuel/oxidant systems non-uniformities of composition must inevitably arise due to non-ideal mixing. There is a need therefore for a laboratory study of the propagation of detonations through composition/concentration changes before their effect on the detonability of an unconfined cloud can be evaluated. The initial problem to be considered in this program is the transmission of a detonation into an inert gas through a free stable interface. The studies are to be performed in a 50mm diameter detonation tube, arranged as in figure 1, using a sliding valve mechanism to generate the free interface. The subsequent motion is to be monitored using pressure and ionisation gauges, microwaves and streak intoferometry.

Preliminary measurements in a rectangular tube 22 X 10mm are presented in figure 2, and show an unexpected phenomenon. When the detonation is incident on a denser acceptor gas a second pressure rise occurs whose magnitude appears to be related to the acoustic mismatch across the interface. This second peak could be significant if the transmitted wave was incident as a second reactive micture. A secondary processing of the gas by this pressure pulse could be a decisive factor under conditions of critical ignition. The present effort is directed towards gathering information on the interaction of a range of detonation systems with various inert gases. By varying the gasdynamic conditions in such a manner it is hoped to elucidate the parameters which govern the transmitted shock profile. Having isolated these factors which control the wave interaction process they can then be related to existing modesl of detonations. The goal at present is thus to deduce the detonation model suitable for use in theoretical treatments of detonation interactions with interfaces.

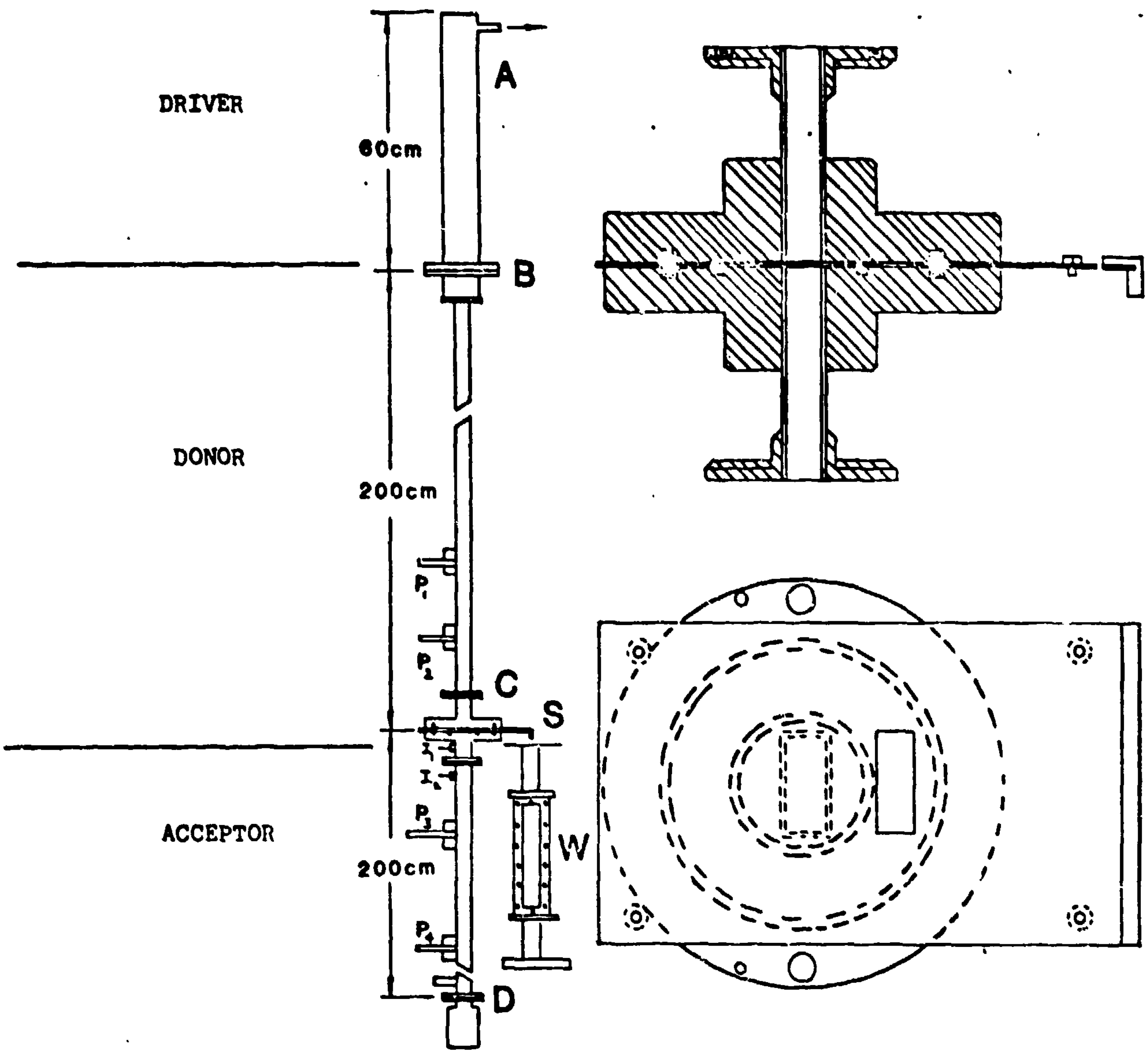

Figure 1. Detonation tube configuration used for interface studies. AB - Driver to ensure rapid establishment of a steady detonation in BC - the donor section. S - slide valve, SD - inert acceptor gas, W - optional window section for optical studies. For horizontal operation the detonation must be initiated within .25 sec. of the valve being opened to avoid buoyancy effects.

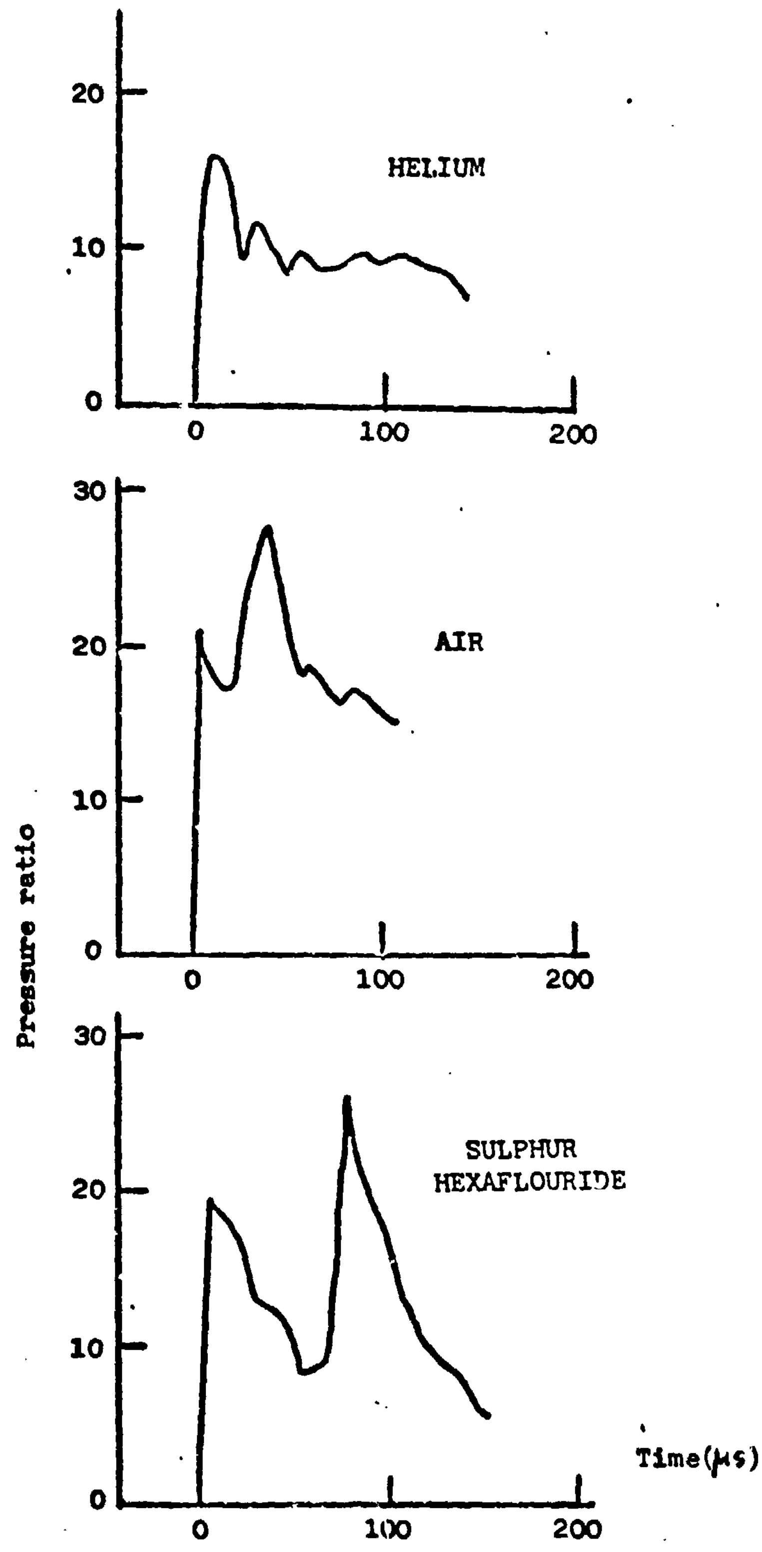

Figure ?. Pressure records at a point 20 cms. into the acceptor gas for an acetylene/oxygen donor. Initial pressure 300 mm. Hg.

IGNITION, COMBUSTION, DETONATION and HEAT ADDITION TO ESTABLISHED FLOWS

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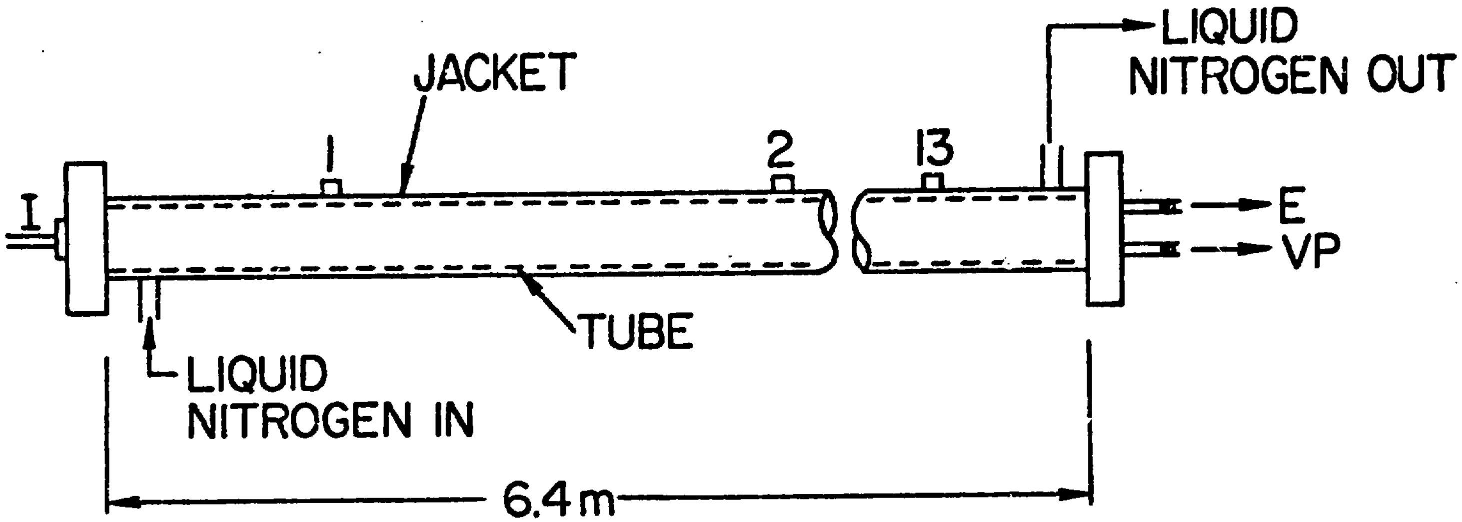
This research is carried out to provide practical relationships which can be used to predict the distances which deflagration waves have to traverse to become detonation waves. Various combustible gas mixtures are studied at various intitial conditions. Although for most practical applications information is needed on the rate of formation of three-dimensional detonation waves including mixutes of condensed phases, in the present effort only the formation of practically one-dimensional waves in gaseous systems is studied. The experiments are carried out in long cylindrical tubes by measuring both the rate at which the combustion wave propagates through the tube and the pressure behind the wave. Of particular interest is the observation that low temperatures of the unburned gas produce extremely short induction distances because this fact may relate to the observed combustion instabilities in the combustion chambers of rocket engines. To elucidate the temperature effect together with that of density hydrogen-oxygen-third gas mixtures are burned in a 6.4 long tube at various initial temperatures and pressures. The results show that the induction distances of these mixtures decrease moderately as the initial pressure is increased. Previous studies with hydrogen-oxygen and hydrogen-air mixtures have shown that the induction distances of these mixtures decrease drastically when their initial temperature is lowered. This observation is in agreement with the large increase in energy transfer from the burned gas to that behind the wave according to theoretical calculations which also reveal that an increase of the initial pressure scarcely affects the energy transfer. To assess the effect of flame propagation rate on the transition from deflagration to detonation the flame propagation rates of the mixtures of interest will also be measured at low initial temperatures. Results at room temperature are shown in Fig. 4 and a schematic sketch of the apparatus is depicted in Fig. 3. A convergent nozzle burner is used to obtain laminar flames even at fairly high Reynolds numbers of the unburned gas flow at the burner port.

A new combustion tube has been designed and is under construction to study the effect of heat addition on the upstream pressure of an existing air flow. This study is to examine the potential effect of fuel flow changes on compressor stall of turbojet engines.

DRAWING OF COMBUSTION TUBE



I- INLET AND IGNITER ASSEMBLY

1-13 DETECTION PROBE LOCATIONS

E- EXHAUST

VP- VACUUM PUMP

Figure 1

Combustion Tube Configuration

Table 1

Induction Distances

Third Gas	Initial Pressure (atm.)	Induction Distance (meters)
$\frac{1}{2}CO_2$	.5	4.75
N_2	.5	4.75
He	.5	5.75
Ar	.5	3.20
$\frac{1}{2}CO_2$	1.0	3.75
N_2	1.0	3.25
He	1.0	3.25
Ar	1.0	2.25
$\frac{1}{2}CO_2$	2.0	3.50
N_2	2.0	3.10
He	2.0	2.80
Ar	2.0	1.75

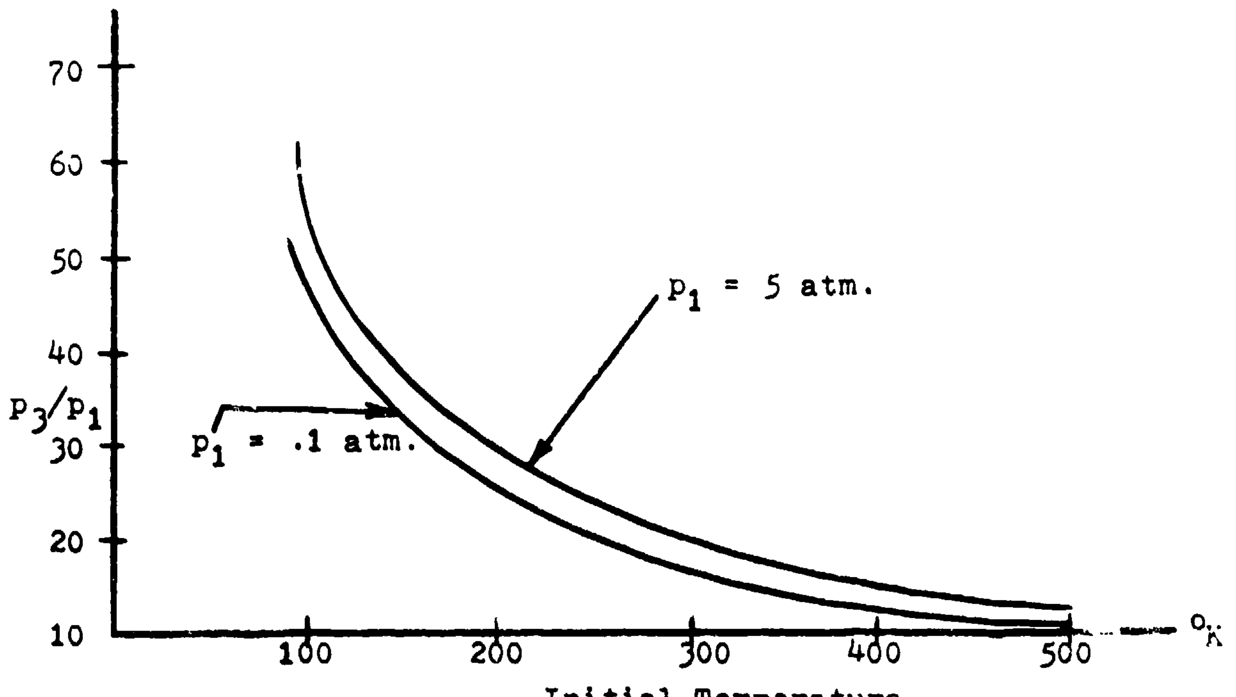


Figure 2

p_3/p_1 vs. T_1 For $\frac{1}{2}O_2 + H_2 + He$

Fig 3 APPARATUS FOR MEASURING FLAME PROPAGATION RATES OF COMBUSTIBLE GAS MIXTURES AT LOW TEMPERATURES

FLAME SPEED MEASUREMENT SYSTEM

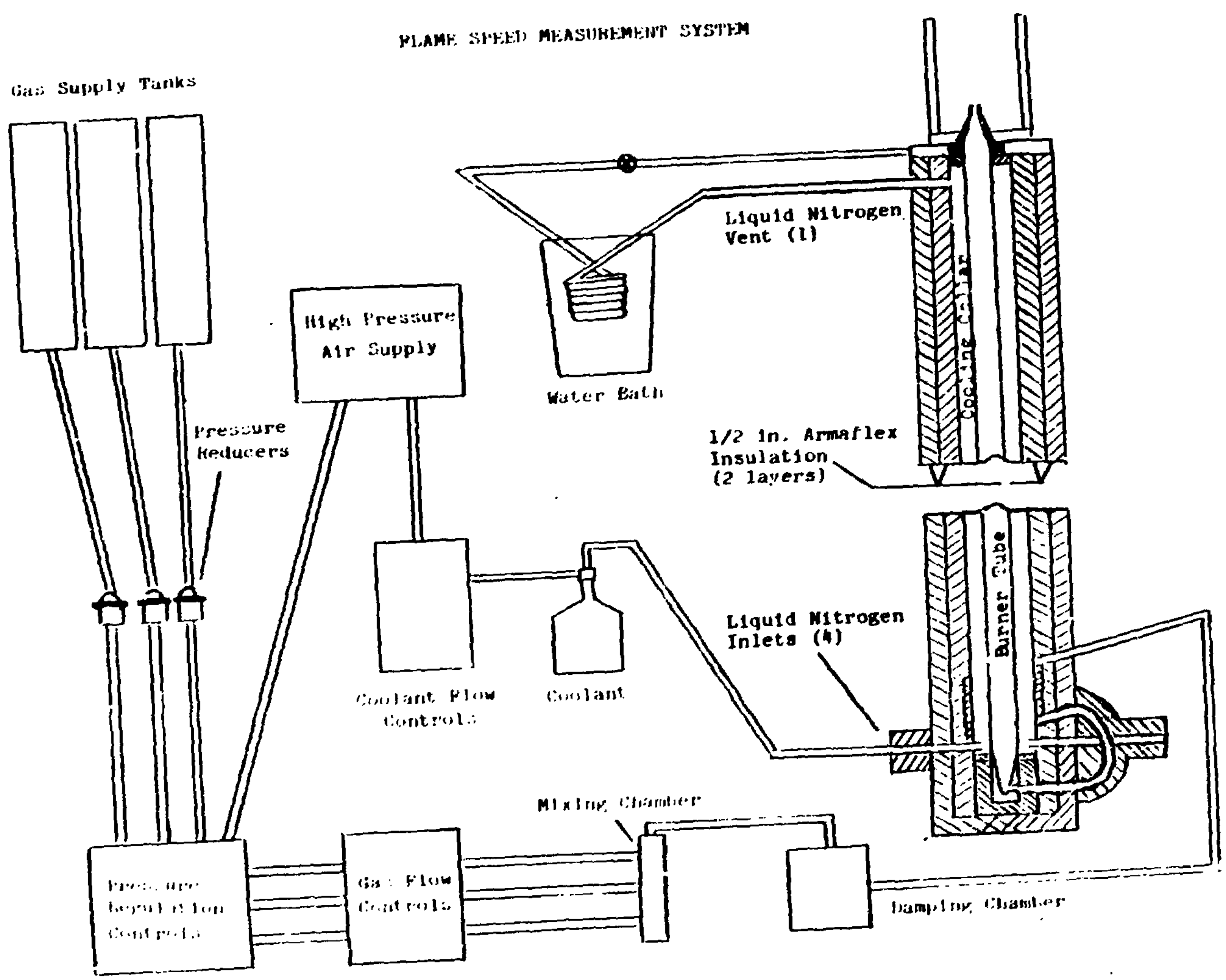
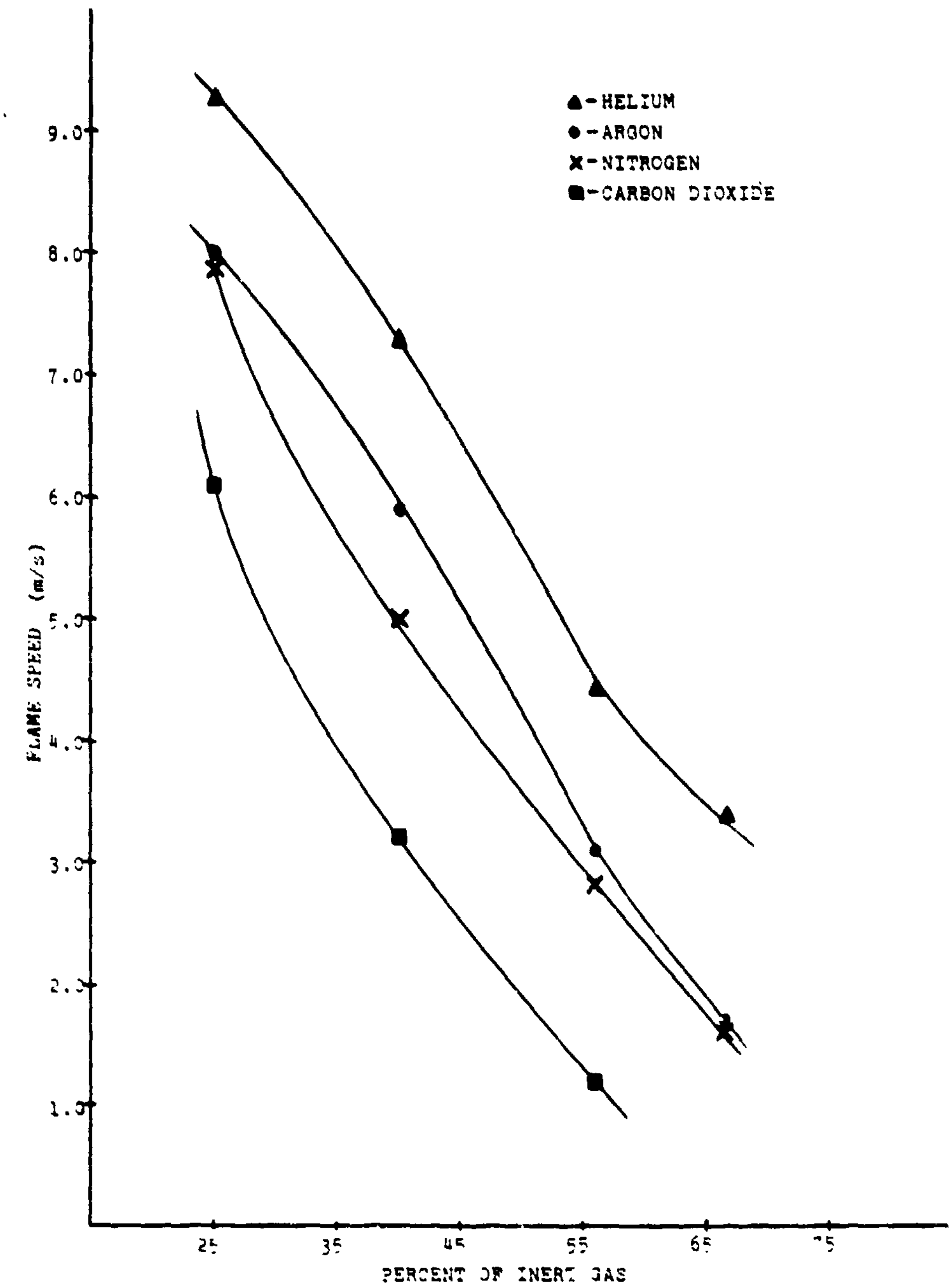


Fig 4 FLAME PROAGATION RATES OF VARIOUS H_2-O_2 THIRD GAS MIXTURES AT ROOM TEMPERATURE



THEORETICAL MODELING AND PREDICTION OF DETONATION PROPERTIES IN DISPERSED POWDERED HIGH EXPLOSIVE - AIR CLOUDS

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(AFOSR-81-0230)

ABSTRACT NOT AVAILABLE

ACCIDENTAL FUEL AIR CLOUDS, THEN SHAPES AND BURNING PROPERTIES

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ABSTRACT NOT AVAILABLE